Synchronous Link Converter and its Application to Electric Traction

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Certificate

Certified that the work contained in the thesis entitled "*Synchronous Link Converter and its Application to Electric Traction*", by Mr. *Frederick L.*, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

The present work formulates the design method for single phase Synchronous Link Converter, which is widely used in modern *ac* motor traction drive systems, low power industrial *ac* motor drive systems, UPS systems and Var compensators. The experimental results have also been presented. The Thesis reviews the modern *ac* motor traction drive powered from 25 kV, 50 hz single phase system, which has become state of the art technology for Electric Locomotives / Motor Coaches. The simulation results to investigate the performance of Synchronous Link Converter when used as a front end converter in modern regenerative *ac* motor, Motor Coach has been presented.

Dedicated
to
my Parents

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Chapter 1

Introduction

1.1 Introduction :

In the field of electric traction, the *ac* electrification at commercial frequency began during the year 1955. The overhead catenary supply was fed at 25.0 kV, 50 hz, single phase supply. Such a system needed power conversion on the Locomotives / Motor coaches for feeding the *dc* traction motors.

Initially the power conversion was done by means of mercury arc rectifier. The maintenance cost of mercury arc rectifier was very high. In order to overcome this drawback, the semiconductor rectifier system was introduced. Such systems are fed from the overhead catenary supply through a step down transformer. The transformer has a single primary winding and multiple secondary windings, each winding feeding a single phase semiconductor diode bridge rectifier. The primary winding has multiple tappings and an on load tap changer for varying taps on the transformer without any voltage surges. The diode bridge rectifier feeds the *dc* traction motors.

Such system has quasi continuous control of the tractive force / speed. This affects the utilization of maximum available adhesion. Also with such system the regeneration was not possible, resulting in considerable wastage of power in the dynamic braking resistors, the reduced life and the increased maintenance of brake blocks, wheel tyres, dynamic braking resistors and braking equipments. The presence of tap changer requires frequent maintenance and is susceptible to frequent failures.

The multistage phase controlled converters operating in sequence control and the pulse width modulated converters were used for obtaining the continuous control of tractive force / speed These schemes however require a reactive power compensator and a passive harmonic filter at the input, for improving the power factor and to avoid the injection of harmonic currents into the catenary supply

Although these schemes ensured the better utilization of adhesion, the system has drawback due to the use of *dc* traction motors such as - the increased maintenance due to presence of commutator and brush gears, comparatively lower torque to weight ratio, lower operating speeds, lower operating voltage, lower efficiency compared with the *ac* traction motors The ripple in *dc* link current affected the performance of *dc* traction motors Also the regeneration was not economically attractive with these schemes

To overcome these drawbacks, the three phase *ac* motors has been employed Such a drive has several important features like regenerative braking capability, very little maintenance and down time, better utilization of the available adhesion, higher average speed, higher torque to weight ratio, higher operating voltage and higher efficiency

Both the Synchronous motors and the Asynchronous induction motors are used in the three phase *ac* motor traction drives These motors are fed from either a Voltage Source Inverter (VSI) or a Current Source Inverter (CSI) However the modern 25 0 kV, 50 hz single phase *ac* electric traction favoured the use of VSI - Squirrel Cage Induction Motor Drives for electric traction application

Such modern electric traction drives require a bidirectional front end converter The Synchronous Link Converter which has this capability permits realization of an economic regenerative *ac* motor traction drive The use of Synchronous Link Converter as a front end converter will ensure, near sinusoidal input current, reduced harmonic current injection into the overhead catenary supply and near unity power factor operation under forward and reverse power flow conditions

1.2 Objective of the Thesis :

The objective of the thesis is to study the performance of Single phase Synchronous Link Converter, establish its design requirements and investigate its performance when used with 25 0 kV, 50 hz, single phase *ac* regenerative traction drive system

1.3 Outline of the Thesis :

Chapter 2 gives review of the Modern AC Motor traction Drive, powered from 25 0 kV, 50 hz, single phase *ac* supply The drives fed from the voltage source inverters and the current source inverters and employing the Synchronous motors and the Induction motors have been covered

Chapter 3 gives the analysis of single stage single phase Synchronous Link Converter The design requirements and the simulation results are presented for forward and reverse power flow conditions

Chapter 4 deals with the experimental verification of a simple single stage single phase Synchronous Link Converter The experimental waveforms of the control circuit and the power circuit for demonstrating the unity power factor operation with nearly sinusoidal source current are presented

Chapter 5 gives the applications of Synchronous Link Converters as a front end converter in a 25 0 kV, 50 hz, single phase *ac* electric traction system The comparison of single stage, two stage, three stage and four stage Synchronous Link Converters are presented The effects of variation of carrier frequency, synchronous link inductance, power out put from the converter, on the psophometric disturbance current characteristics are presented

Chapter 6 gives the overall conclusion of thesis with scope for future work

Chapter 2

AC Motor Traction Drives - A Status Review

2.1 Introduction :

Due to the advantages associated with *ac* motors, the *ac* motor drives are replacing *dc* motor drives The modern *ac* motor traction drives have several important features such as regenerative braking capability, very little maintenance and down time, near unity power factor operation, nearly sinusoidal current, good adhesion, higher average speed and higher efficiency

2.2 Important features of an Electric Traction drive

The following are some of the important features of an electric traction drive system [1]

1 For economic reasons, the 25 kV, 50 hz *ac* traction employs only single phase supply although the rating of locomotive is as high as 6000 hp

2 The traction supply is weak in nature and hence the voltage is subjected to fluctuations

3 As the traction supply is weak in nature, the reactive power has very adverse effect It is essential that the power factor is not allowed to be lower than 0 8

4 The use of electric brakes reduces wear and tear on the track, wheels and brake shoes, thereby increasing their life substantially

5 The dynamic braking is generally used But when the energy saving is sufficiently large to justify additional cost of the drive, the regenerative braking is preferred

6 The regenerative braking is generally combined with the dynamic braking

7 The use of controlled rectifier results in the generation of harmonics, which are injected into the source This results in the following adverse effects

   (a) The high frequency harmonics cause the interference with communication line

   (b) The low frequency harmonics may enter into the track circuits, leading to mal operation of the signals

   (c) They cause sharp fluctuations in the supply voltage

2.3 Advantages of ac motor traction drives over the dc motor traction drives :

The modern traction drives generally use three phase induction motor as traction motor The *ac* motor drive has following advantages

1 Three phase induction motors are robust and have high torque to weight ratio

2 Simplified and reduced maintenance because of the absence of commutator and brush gear as in *dc* motor drives

3 The full use of available adhesion between the wheel and the rail, because of the naturally steep torque - speed characteristics of induction motor

4 The induction motor has a good regeneration capability

5 Due to absence of the commutator, the motor windings can be designed for higher voltages This results in more favourable design of the other components such as inverter, converter, transformer secondary etc

6 At the same power level, induction motor is lighter than *dc* motor This results in relatively smaller unsprung mass of the truck giving a good riding characteristics and results in a low rail stress

7 The three phase induction motor has improved efficiency and reliability in operation than *dc* motor

8 With three phase drive, the electric braking down to standstill is possible

2.4 Suitability of VSI and CSI drive for traction application :

The three phase *ac* induction motor should be fed from a three phase supply capable of delivering steplessly variable frequency and voltage The Current Source Inverter (CSI) and the Voltage Source Inverter (VSI) are available to meet this requirement The important relative merits and demerits of CSI and VSI drives in relation to traction are as follows [2] [3]

1 CSI drive do not suffer from the shoot through fault which is common in VSI drives

2 The regenerative braking capability is inherent in a CSI drives fed from a line commutated fully controlled converter or a PWM fully controlled converter and in VSI drive powered from a Synchronous Link Converter If the *ac* supply fails the regenerative braking will not be possible in both the drives Under such conditions, a VSI drive can use dynamic braking but the same is not possible with CSI drive

3 The presence of large value inductance in the *dc* link of a CSI drive results in the slower dynamic response compared to PWM VSI drive Consequently VSI drive has better adhesion (i e the lower possibility of wheel slip)

4 When the source is *dc* a PWM VSI drive will be cheaper compared to a CSI drive of the same rating Also the requirements of the large commutation capacitors and a large *d c* link inductor which is oversized to prevent saturation,

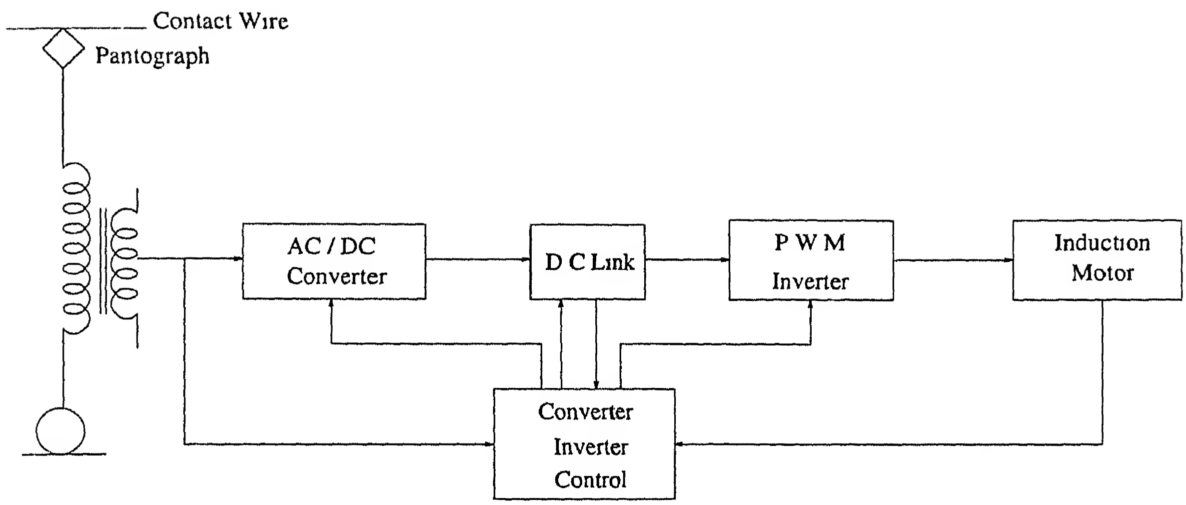


Figure 2 1 A popular AC motor traction drive

the volume and weight of CSI drive is much higher compared to PWM VSI drive

5 The frequency range of CSI is lower than VSI drive Hence the CSI drive has a lower speed range

6 The CSI is not suitable for multimotor drives Hence each motor is fed by its own inverter and rectifier But a single diode bridge or a synchronous link converter can be used to feed a number of VSI motor system Alternatively a single VSI can feed number of motors

2.5 AC Motor traction drive :

2.5.1 Principle of operation :

The block diagram of a popular *ac* motor traction drive is shown in fig 2 1

The pantograph collects the power for the running locomotive from the overhead line The pantograph is connected to the primary of transformer The isolation and protection devices are provided between the pantograph and the transformer

The traction transformer has a single primary winding and multiple secondary windings for feeding the traction converters The traction transformer is so designed that the percentage impedance of all the secondary windings feeding traction converters are maintained unchanged irrespective of the combined or isolated operation of windings

The traction power converters consists of PWM converters These are connected in series or parallel Each unit is of modular construction with the built in cooling arrangements The converters are controlled in a way to maintain unity power factor, throughout the operating range, with practically zero harmonic injection into the line

The *dc* link consists of a suitable bank of capacitors designed to provide a stable *dc* link voltage for feeding variable voltage and variable frequency inverter (VVVF) in voltage source configuration Alternatively *dc* link may consist of a suitable inductor designed to provide a stable *dc* link current for feeding CSI inverter in current source configuration

The *dc* link decouples the drive from the source The inverter used may be CSI type or VSI type Generally CSI type inverter is used with synchronous motor drives and the VSI type inverter is used with induction motor drives The output of the inverter is connected to three phase traction motors The synchronous motors have higher full load efficiency and power factor than induction motors However compared with induction motors they have higher cost, weight and volume for the same rating and require more maintenance

Generally microprocessor based control systems are used for the converter control, *dc* link control, inverter control, traction motor control, braking control and slip control The microprocessor also performs the task of fault diagnostic and display in addition to the control task.

2.5.2 Control of three phase ac motor traction drives :

Several drives employing the squirrel cage induction motors and the synchronous motors are in use for traction. Variable frequency control is used both for the induction motors and the synchronous motors

The modes of operation of the induction traction drive is shown in fig 2 2 This drive has received wide acceptance

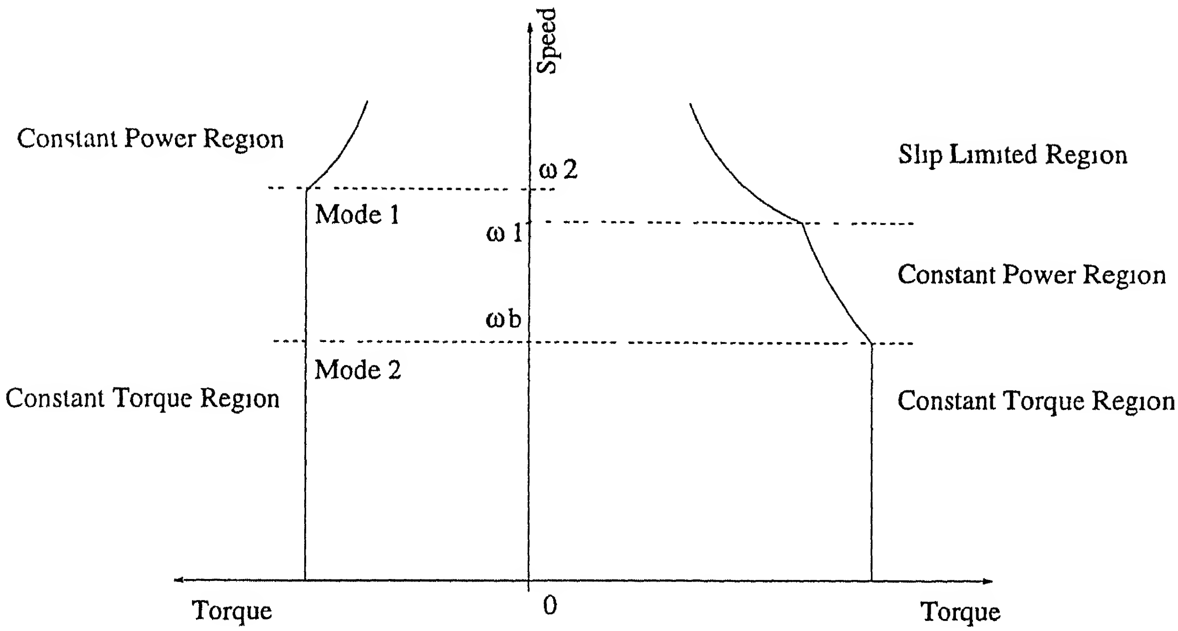


Figure 2 2 Modes of operation of AC motors with VVVF control

When the drive is in motoring region, the characteristic curve has the following three regions [4]

1 Constant Torque region

2 Constant power region

3 Slip limited region

1. Constant torque region :

The constant torque region lies from the standstill to base speed (ω_b). In this region the inverter is operated to supply adjustable voltage and frequency to the motor The motor voltage is adjusted as speed (frequency) changes to maintain a constant flux density in the motor. The motor voltage therefore increases proportionally with the speed (frequency) The frequency of voltage induced in the rotor (slip frequency) is held constant This produces nearly constant torque since the power output is proportional to the speed, the power increases linearly with speed At base speed (ω_b), the *ac* voltage reaches the maximum limit of inverter

2. Constant power region :

In this region, the inverter is operated to supply the adjustable frequency to the motor The voltage is no longer adjustable and the inverter is operated at maximum voltage limit The power output from the motor remains nearly constant This mode of control is extended until point (ω_1), where the motor breakdown torque limit is reached

3 Slip limited region :

In this region, the slip frequency is maintained constant and any increase in the speed is done by reducing the motor current Here the motor current reduces inversely with the speed and the torque decreases inversely as speed squared This characteristic is often referred to as series motor characteristic The torque produced in this region is some what higher than that produced by a *dc* series motor

When the drive is in braking region, the characteristic curve has the following regions of operation [5]

1 Constant power region

2 Constant torque region

1. Constant power region :

In this region, the drive power is held constant to match the inverter maximum power capability This mode is similar to constant power mode during motoring and slip frequency varies proportional to the speed

2. Constant torque region :

When the drive is braking, the constant torque region has two modes of operation

Mode1 : In this region, both the motor voltage and current are varied approximately as square root of speed Hence the power varies directly with speed, as the slip frequency is varied in direct proportion to the speed The power fed back to the source is proportional to the speed, decreasing linearly with speed

Mode2 : In this region, the motor current is held constant as slip frequency is held constant The motor voltage therefore reduces proportionally with the speed(frequency) At low speeds the electric braking is allowed to fade

2.5.3 Requirement of ac Motor traction drive :

1 The source side converter shall ensure a power factor as near unity as possible

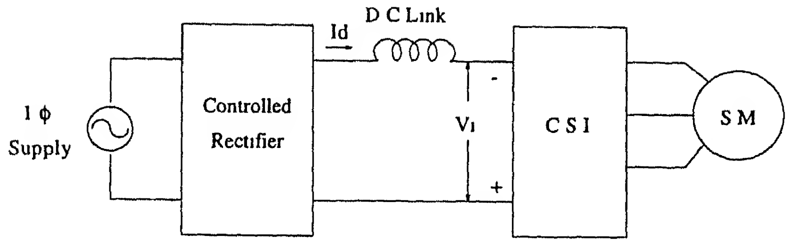


Figure 2 3 Load commutated inverter synchronous motor drive

2 The converter shall be designed in a way to keep psophometric disturbance current within the enforced limit

3 The converter shall be designed in a way, such as not to cause intolerable level of interference to track circuit, signal and telecommunication equipments

4 The power converter/inverter shall ensure a four quadrant operation and regenerative braking shall be available from maximum speed range upto standstill

5 The power converter/inverter shall ensure the full utilization of the available adhesion

6 The inverter shall incorporate beatless control system to suppress beat phenomenon

2.6 Load Commutated Inverter Synchronous Motor traction drive :

2.6.1 Basic principle :

Generally a self commutated synchronous motor drive is used for electric traction drive [6] Fig. 2 3 shows a simple load commutated inverter synchronous motor drive The drive employs two converter termed as source side converter and load side converter The source side converter and the load side converter are both operated in first and fourth quadrants Hence regenerative braking capability is inherent [7]

In a self controlled synchronous motor drive, the following control strategies are generally used [8]

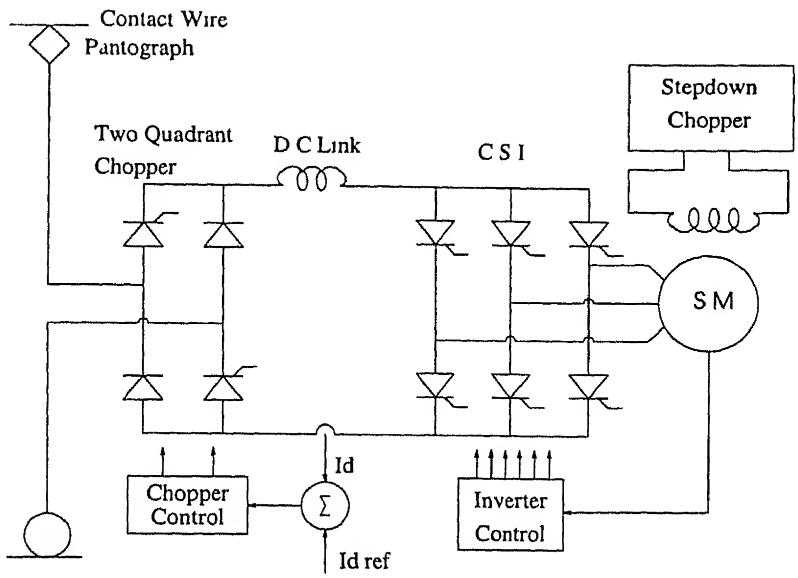


Figure 2 4 Regenerative synchronous motor DC traction drive

1 Constant margin angle control

2 Constant lead angle control

3 Constant no load angle control

In all the above mentioned control strategies the synchronous motor operates with a leading power factor and the thyristors of load side converters are commutated by the motor induced voltages, in the same way as the thyristor of line commutated converter Because the firing is synchronized with the machine induced voltage, the machine always operates in self control mode The source of input to source side converter may be *dc* or *ac*

A load commutated inverter synchronous motor traction drive using thyristors is shown in fig 2.4 Here the input to source side converter is *dc* The current source is formed by a two quadrant chopper(quadrant I and IV), a *dc* link inductor and a current feedback The load side converter is commutated by the back emf of the synchronous traction machine

When the over head catenary is *ac*, the scheme shown in fig 2 5 is used Here current source is formed by source side converter (a controlled rectifier), *dc* link inductor, and the current loop The load side converter is operated in self control mode and with load commutation

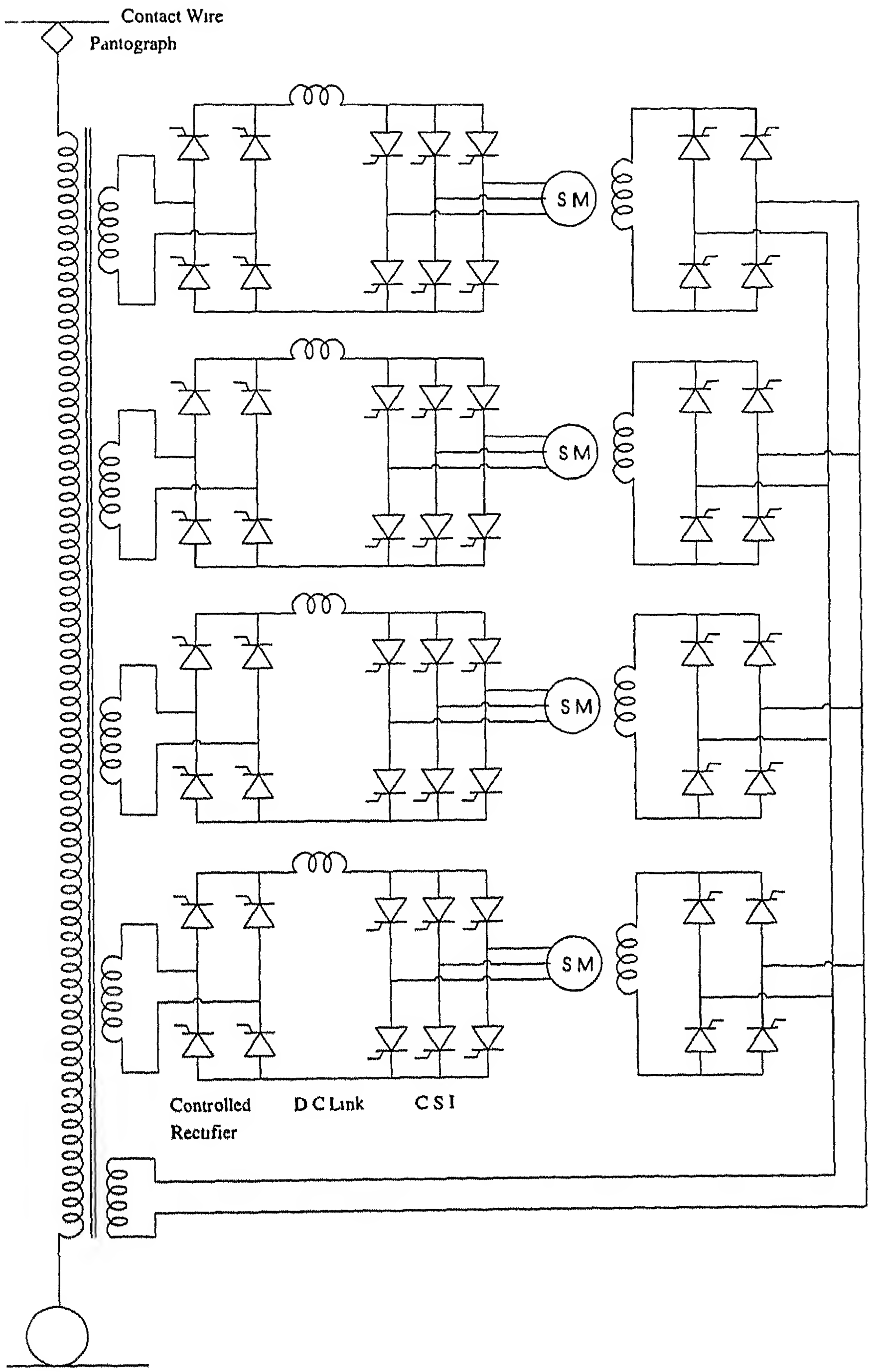


Figure 2 5 Regenerative synchronous motor AC traction drive

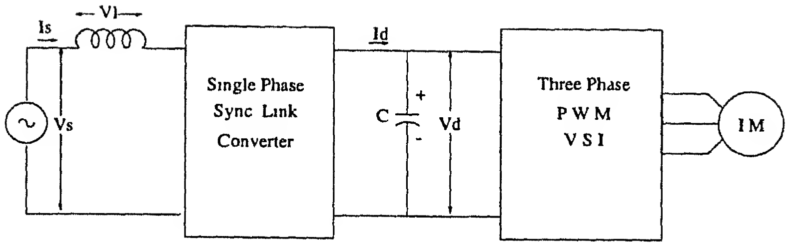


Figure 2 6 Regenerative induction motor drive using synchronous link converter

2.6.2 Control of Load commutated inverter Synchronous Motor Drive :

When the drive is in motoring, the source side converter acts as rectifier and the load side converter acts as an inverter resulting in the forward motoring operation In this mode of operation the average value of V_i (fig 2 3) will be negative and I_d is positive and hence the power flows from *dc* link to the machine giving operation in quadrant I

For braking the drive, the load side converter is controlled in a way, that the average V_i (fig 2 3) will be positive Since the direction of I_d remains unchanged, the power flows from the motor to the *dc* link In this mode of operation the load side converter works as a rectifier and the machine regenerates The source side converter is operated to feed the energy back to the source

In case of the load commutated synchronous motor drive, at low speeds the induced emf will be insufficient to commutate the thyristor of load side converter Therefore at start and for the speed below 10 % of rated drive speed, the commutation load side thyristor is done by forcing the current of conducting thyristors to zero, with the help of source side converter [9]

Alternatively, synchronous motor can be started by employing a simple forced commutation circuit utilizing a single capacitor and two auxiliary thyristors for entire inverter [10]

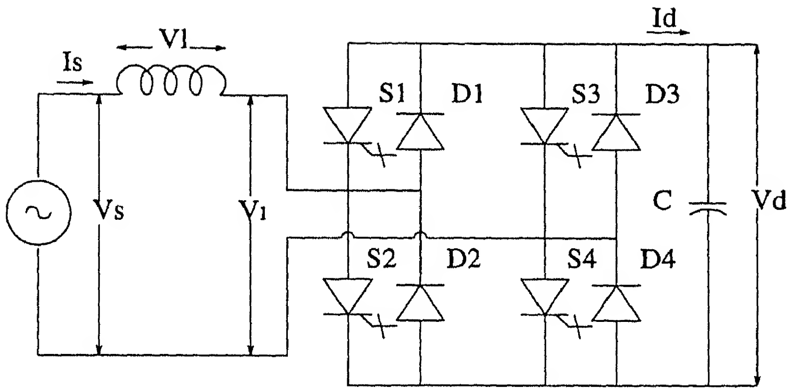


Figure 2 7 Single phase synchronous link converter

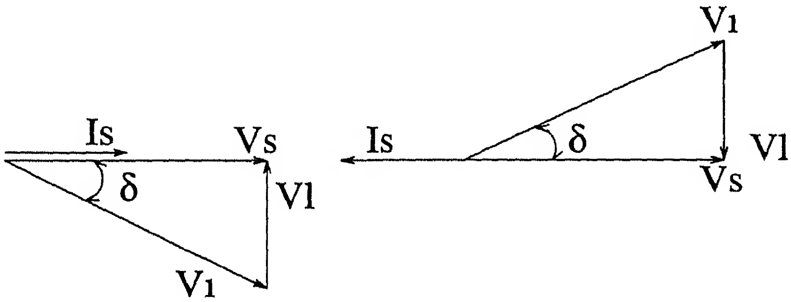


Figure 2 8 Phasor diagram of a single phase synchronous link converter

2.7 VSI - Squirrel Cage Induction Motor Drive

2.7.1 Basic Principle :

A regenerative induction motor drive using a synchronous link converter is shown in fig 2 6 The Synchronous link converter permits realization of an economic regenerative a c drive with nearly unity power factor and a low harmonic content in the source current [11] The converter circuit is shown in fig 2 7

When the single phase voltage source inverter is operated with the pulse width modulation, it produces the voltage V_i If the voltage V_d is maintained constant, then the magnitude of V_i may be varied by adjustment of the modulation index of the converter The phase of V_i w r t V_s can be altered by changing the phase of the firing pulses of the inverter, w r t the phase of V_s By appropriately choosing the magnitude and the phase of V_i for a given I_s, the phase angle between V_s and I_s can be adjusted to a desired value

Fig 2 8 shows the phasor relationship of vectors when the phase angle between source voltage V_s and source current I_s are 0^o and 180^o respectively In either case the power factor is unity When the phase angle is zero the converter works as a rectifier transferring power from *ac* source to the *dc* link In this mode of operation, current I_d has a positive direction When the phase angle is 180^o current I_d reverses and the power flows from the *dc* link to the source and the converter works as an inverter Because of the operation of converter with pulsewidth modulation, the source current has a low harmonic content

Fig 2 9 shows three phase regenerative traction drive using Synchronous link converter, and PWD inverter Here two Synchronous link converters are connected in parallel feeding an inverter, which in turn feeds three induction motors connected in parallel Two such units are fed from a common transformer [12] [13]

Depending upon the power level IGBT / GTO can be used in the construction of synchronous link converter In the case of Motor coaches , IGBT's can be used both in Synchronous link converter and inverter Since the IGBT,s can be operated at a frequency of 2 5 khz, the harmonics in source current can be reduced to a smaller value We can use sinusoidal PWM, current controlled PWM or vector PWM for both converter and inverter In case of locomotive, because of the large power levels, GTO have to be used Since at high power levels GTO thyristors are operated around 400 hz, generally sinusoidal PWM is used and more than one converter is operated in parallel to keep the hormoncs in the source current within acceptable limits

2.7.2 Control of VSI - Squirrel cage Induction Motor Traction drive :

The modern VSI squirrel cage induction motor traction drives are generally torque controlled drives. The drive is started with reduced voltage and frequency This frequency reduction improves the motor power factor and increases the torque per ampere at the start Hence the rated torque is available at the start, and the drive is accelerated to its operating speed The drive is operated in a way described in section 2 5 2 Here the power transfer is from source to the load

For transferring the operation from the motoring to regenerative braking, the inverter frequency is reduced A reduction of the inverter frequency makes the

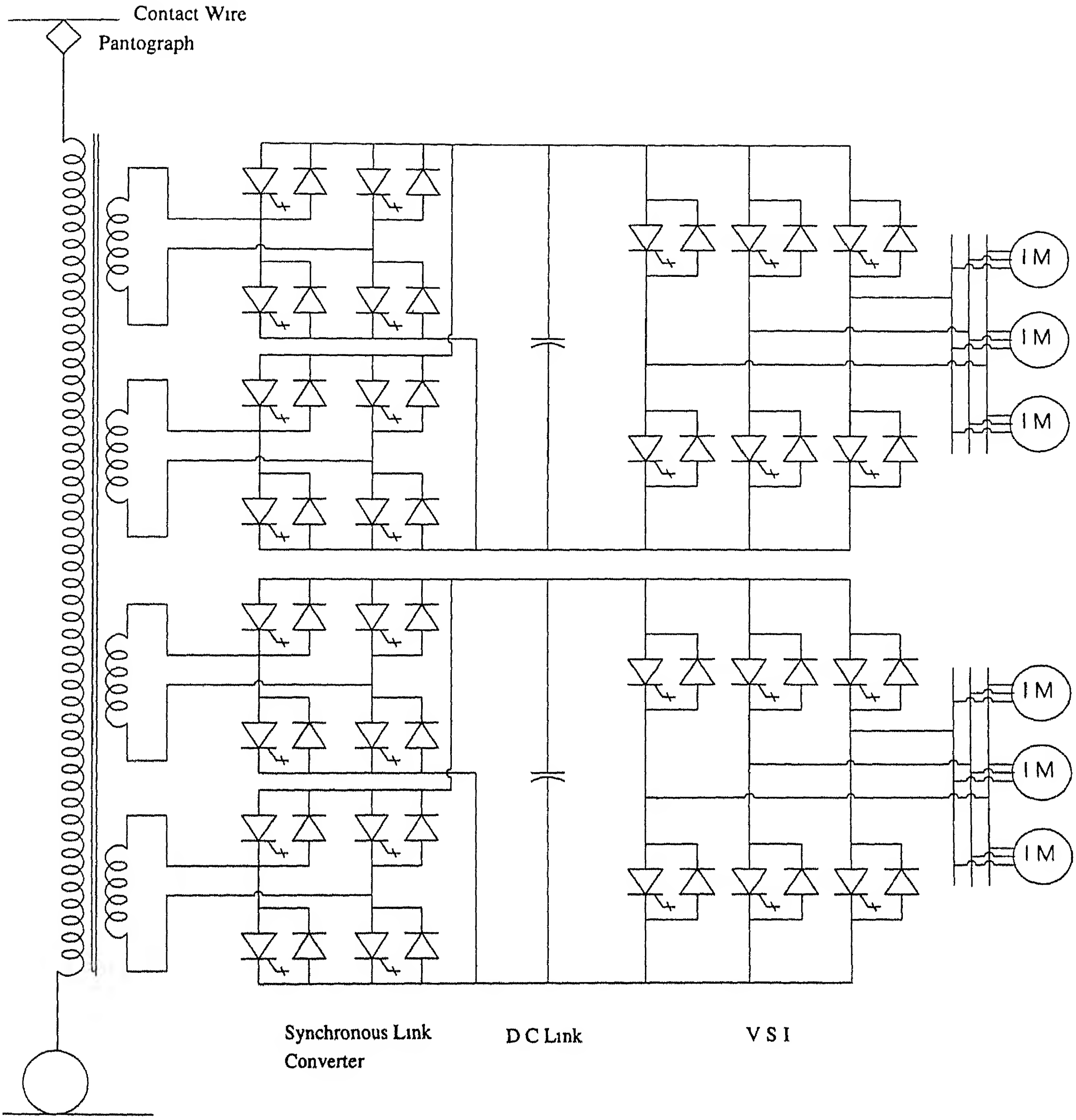


Figure 2 9 Regenerative traction drive using synchronous link converter

synchronous speed less than the motor speed and transfers operation from quadrant I to quadrant II Here the power flows from motor to *dc* link and from *dc* link back to the source The inverter voltage and the frequency is reduced to brake the machine to zero speed

For speed reversal, the phase sequence of inverter voltage is reversed by interchanging the control signals between the switches of any two legs of inverter In the scheme described above, when the source is unable to take back the regenerated power, the dynamic braking scheme can be used For this purpose a braking resistor is provided in series with switch across the *dc* link capacitor The generated power charges the filter capacitor and its voltage rises When the voltage reaches a prescribed maximum limit, the switch is turned on, connecting the braking resistor across the capacitor The energy generated and the energy supplied by the filter capacitor are dissipated in the braking resistor When the capacitor voltage reaches the prescribed minimum limit the switch is turned off Again the capacitor voltage starts rising and the cycle repeats Thus only that portion of the regenerated energy is dissipated by dynamic braking resistor which cannot be accepted by the source

Generally the Indirect current control technique is used with synchronous link converters for ac motor traction drive

With the above mentioned control technique, for a given value of reference, the power input to the converter has a fixed value When the load on the converter is decreased, then there would be unbalance between power input and the power output Hence a closed loop control is provided across the synchronous link converter fig 2 10

2.8 Harmonic Reduction and Control of Torque Pulsation :

The line side converter generates current harmonics which are injected into the overhead lines Hence the measures are to be taken to keep the harmonics below a desired limit Some of the methods used with VSI Squirrel cage induction motor drives are

1 By series / parallel connection of converters the supply current harmonics can be reduced considerably If 'n' converters are put in series/parallel and if the

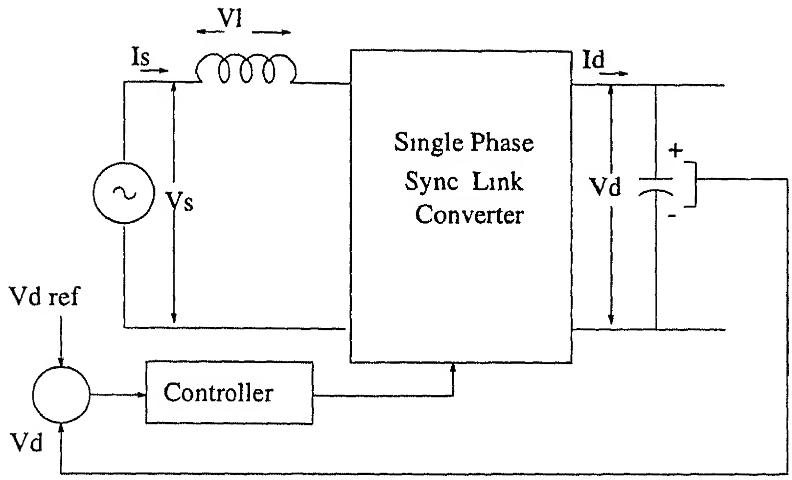


Figure 2 10 Closed loop control around a synchronous link converter

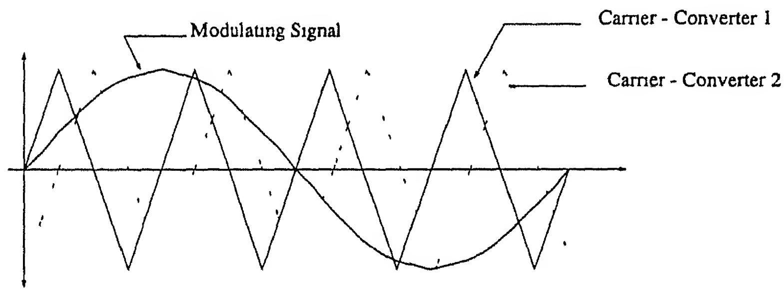


Figure 2 11 Carrier waves for two converters operating in parallel

carrier signals of the individual converters are equally displaced within one half of carrier period interval by an angle π/n radians, then some of the reflected harmonics cancel on the primary side of transformer The ripple frequency of the primary current has a frequency $(n \times f_c)$, where 'n' is the number of converter put in parallel/series and f_c is the carrier signal frequency [14] [15]

For example if the synchronous link converter is realized by using two GTO converters, say converter I and converter II in parallel, then the firing of the GTO thyristors in converter I and converter II can be done by using a common modulating signal and the triangular carrier wave phase shifted from each by an angle 90 deg (because n = 2) as shown in fig 2 11

2 By using three level converter as compared to two level converter [16]

3 By employing switched electronic compensator which generates an exact replica of the harmonic currents It is fed into traction transformer to produce harmonic counter emf This ensures that the transformer main flux is sinusoidal, and hence the induced voltage in the primary The line current is low pass filtered by the transformer leakage inductance and assumes a sinusoidal waveform [17]

For reducing the harmonic in the inverter output voltage and hence to minimize the torque pulsations, the inverters can be connected in parallel They share the common *dc* link voltage and *ac* output terminals of the respective phases are connected through an inter phase reactor The mid point of the inter phase reactor is connected to the respective phases of an induction motor The inverters operated with common modulating signals, but the carrier signals of individual inverters being equally displaced within carrier period interval Also when the traction drive is in constant torque region, the inverter is operated in asynchronous mode to limit the torque pulsation [18]

2.9 Advantages of VSI Squirrel Cage Induction Motor Traction Drive :

The VSI squirrel cage induction motor traction drive has the following advantages

1 Unity power factor

2 Low harmonic content in the source current

3 Regenerative braking capability at low cost

4 Smooth acceleration due to absence of low speed torque pulsation

5 Efficient and quiet operation due to low harmonic content in the motor input voltage

6 Good adhesion due to fast dynamic response and absence of torque pulsations

7 Multi motor drive possible due to use of VSI

8 Regenerative braking capability offers energy saving

9 The dynamic braking can be resorted in the event of catenary failure due to use of VSI

10 Improved energy efficiency

11 Reduced maintenance cost

12 Reduction in the size and weight of the traction circuit equipments

2.10 Conclusion :

The ac motor traction drives are superior to dc motor traction drives The recent advances in Power Electronics, drive control techniques and availability of micro-controllers for control and fault diagnosis has enabled the realization of the traction drive with high efficiency, high level of performance and low down time

Chapter 3

Design and Analysis of a Synchronous Link Converter

3.1 Introduction :

The power conversion from *ac* to *dc* has so far been dominated by uncontrolled rectifier or line commutated, phase controlled rectifiers Such converters have the inherent drawbacks such as harmonics in input current and in output voltage and low input power factor particularly at the low output voltages Several applications require the front end *ac* to *dc* converters, having both rectifying and regenerating abilities Dual converters were used under such requirements, complicating the power and the control circuits The Synchronous Link Converter can be used as front end converter under such applications requiring rectifying and regenerating abilities

The Synchronous Link Converter have the advantage of taking near sinusoidal input current at unity power factor This chapter deals with the design and analysis of single phase Synchronous Link Converter The Electric Traction uses single phase supply even at high power level Also many low power *ac* / *dc* drives , UPS system operates from single phase supply These low / high power drive system at present require Synchronous Link Converter as front end converter

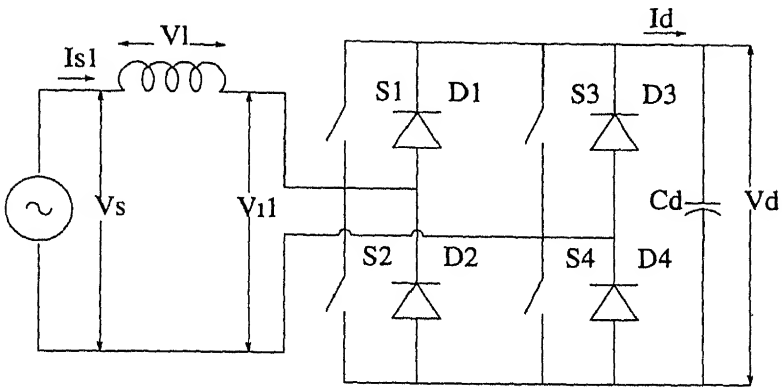


Figure 3 1 Basic single phase Synchronous Link Converter

3.2 Principle of a Synchronous Link Converter :

Fig 3 1 shows the circuit of Synchronous Link Converter The switches S1, S2, S3 and S4 are all self commutating switches The circuit resembles a Voltage Source Inverter When these switches are operated with a known pulse width modulation technique, it produces a voltage V_i at converter input terminal If the *dc* link voltage V_d is maintained constant then the magnitude of converter input voltage can be varied by the adjustment of modulation index of the converter The phase of the voltage V_i with reference to the supply voltage V_s can be altered by changing the phase of switching pulses of the switch w.r t the phase of V_s

Let i_s be the converter input current and L_s be the inductance on source side Then

$$v_s = v_l + v_i \tag{3 1}$$

$$and \;\; v_l = L_s \frac{di_s}{dt} \tag{3 2}$$

Assuming v_s to be sinusoidal, fundamental component of the converter input voltage v_i and the fundamental component of converter input current i_s can be expressed as phasors V_{i1} and I_{s1} respectively

Let V_s be chosen as reference phasor i e

$$V_s = V_s e^{j0} \tag{3 3}$$

and ω be the supply frequency in radians i e

$$\omega = 2\pi f \tag{3 4}$$

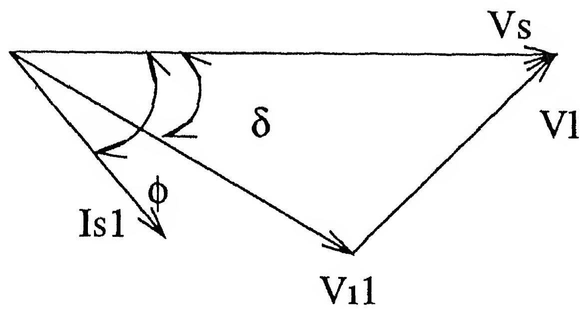


Figure 3 2 Phasor diagram of a basic Synchronous Link Converter

$$V_s = V_{i1} + V_l \tag{3 5}$$

$$V_l = jwL_sI_{s1} \tag{3 6}$$

The phasor diagram corresponding to equations 3 5 and 3 6 is shown in fig 3 2, where the supply current I_{s1} lags the supply voltage V_s by an angle ϕ

The real power transferred from the source to converter is given by the following equation

$$P = V_sI_{s1}cos\phi \tag{3 7}$$

From the phasor diagram of fig 3 2 we get

$$cos\phi = \frac{V_{i1}sin\delta}{V_l} \tag{3 8}$$

Substituting for $cos\phi$ in equation 3 7 we get

$$P = \frac{V_sI_{s1}V_{i1}sin\delta}{V_l} \tag{3 9}$$

$$P = \frac{V_sV_{i1}sin\delta}{X_s} \tag{3 10}$$

where,

P = Real power supplied to the converter in watt

V_s = rms value of the ac supply voltage in volts

V_{i1} = rms value of the fundamental component of the converter input voltage in volts

δ = the power angle between voltage phasor V_s and V_{i1} in radians
X_s = reactance of the source side inductance L_s in ohms
ϕ = power angle in radians
The reactive power supplied by the *ac* source is

$$Q = V_s I_{s1} sin\phi \tag{3 11}$$

From the phasor diagram of fig 3 2 we get

$$sin\phi = \frac{V_s - V_{i1}cos\delta}{V_l} \tag{3 12}$$

Substituting for $sin\phi$ in equation 3 11 we get

$$Q = \frac{V_s^2}{X_s}\left[1 - \frac{V_{i1}cos\delta}{V_s}\right] \tag{3 13}$$

Where Q is sum of the reactive power absorbed by the converter and the inductance L_s

From equations 3 10 and 3 13 we find that for a given supply voltage V_s and the chosen supply inductance L_s, one can obtain the desired values of real and reactive power by controlling magnitude and phase of the converter input voltage V_{i1}

From equation 3 8 we have

$$I_{s1}cos\phi = \frac{V_{i1}sin\delta}{X_s} \tag{3 14}$$

Similarly from equation 3 12 we have

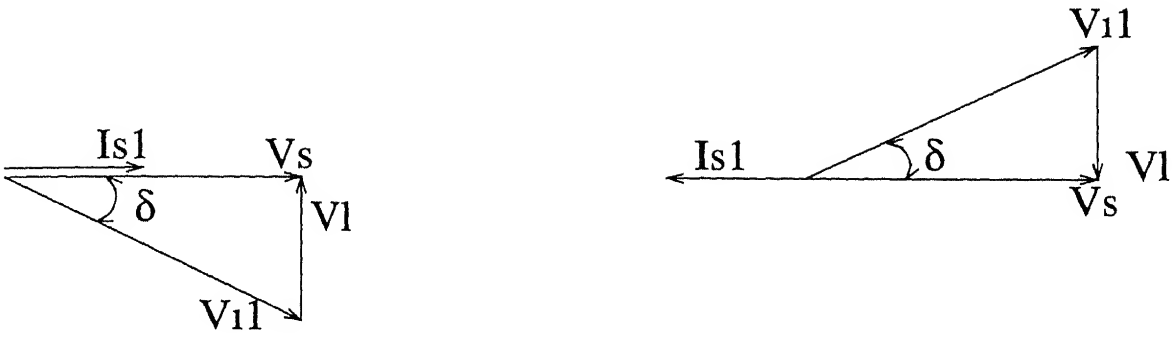
$$I_{s1}sin\phi = \frac{V_s - V_{i1}cos\delta}{X_s} \tag{3 15}$$

If we desire unity power factor at the converter input terminal, then the reactive power drawn from the supply has to be zero Hence from equations 3 14 and 3 15, we have

$$I_{s1}X_s = V_{i1}sin\delta \tag{3 16}$$

$$V_s = V_{i1}cos\delta \tag{3 17}$$

The phasor diagram for unity power factor operation under forward and reverse power flow is shown in the fig 3 3a and fig 3 3b respectively



a b

Figure 3 3 Phasor diagram for forward / reverse power flow at unity power factor

Figs 3 3 resemble the vector diagram of Synchronous machine supplying or regenerating from a active load The supply inductance L_s separates the supply voltage V_s and the converter input voltage V_i and thus works as a synchronous link

Synchronous Link Converter works in boost mode The output *dc* voltage is fixed and is higher than the supply voltage Thus a fixed *ac* input voltage is converted into a fixed output *dc* voltage The output power is controlled by controlling the *dc* link current Due to the operation of Synchronous link converter with PWM switching pattern, it has a sinusoidal input current and a high quality *dc* output voltage These features results in the smaller size input and output filters and hence result in higher efficiency

3.3 Control Technique for a Synchronous Link Converter :

The Synchronous Link Converter uses the following current control technique -

1 Hysteresis current control

2 Predictive current control with fixed switching frequency

3 Indirect current control

4 Load current control

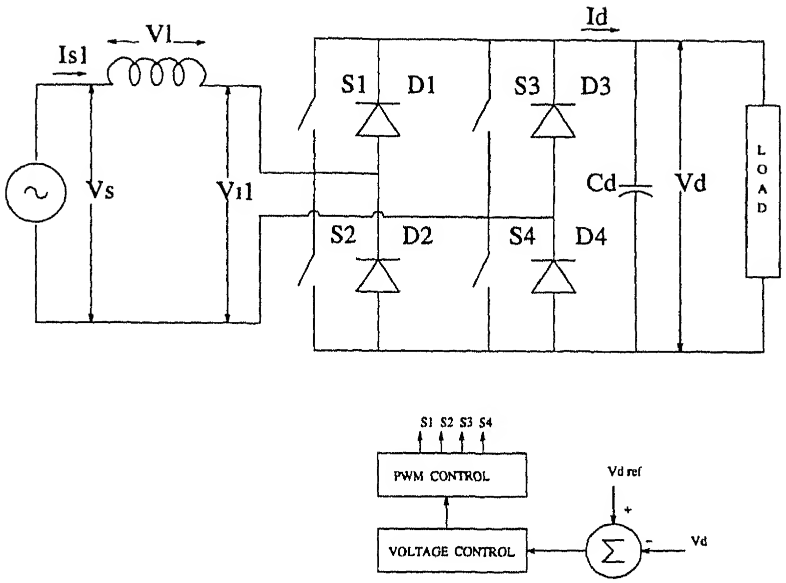


Figure 3 4 Basic control scheme of a Synchronous Link Converter

In the case of Electric Traction, where the power involved is very high generally GTO thyristors are used in the construction of Synchronous Link Converter The switching frequency used is also low around 450 hz Also more than one converters are connected in parallel in order to keep the harmonics within acceptable limits and they are operated with indirect current control

3.3.1 Indirect Current Control :

In the case of Synchronous Link Converter it is required to regulate the *dc* link voltage by matching the input power to converter with the power demand from the *dc* link This power balance is to be maintained at unity power factor for either direction of power flow

In case of the indirect current control scheme, the *ac* input current is indirectly controlled by the standard sinusoidal PWM, which essentially modulates the fundamental component of voltage at the converter input terminals The equations governing the current control, neglecting resistance of the synchronous link inductor and source can be written as

$$V_{i1} cos\delta = V_s + I_{s1} X_s sin\phi \tag{3 18}$$

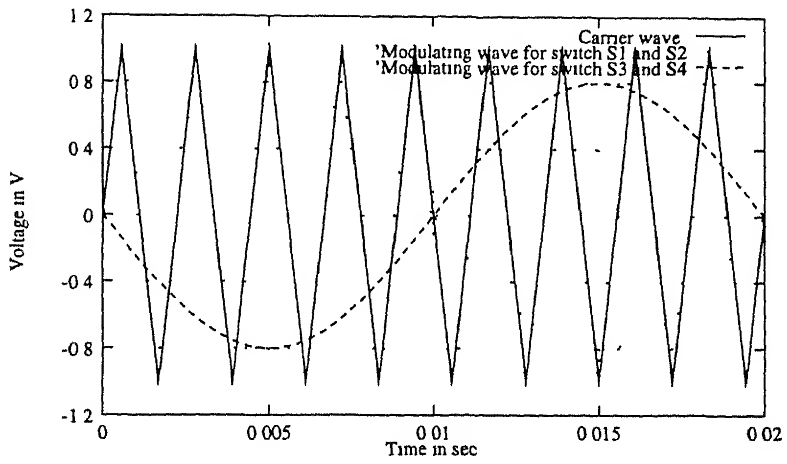


Figure 3 5 Principle of the Converter control

$$V_{i1} sin\delta = I_{s1} X_s cos\phi \tag{3 19}$$

The schematic diagram of such a scheme is shown in fig 3 4 The error in *dc* link voltage V_d from the set reference V_d^* defines the input current required Assuming a simple SPWM technique, the inphase and the quadrature components of the modulating signals are obtained and added to get the modulating signal displaced at δ degrees This modulating signal controls the necessary fundamental component of converter input voltage V_{i1} and current I_{s1} at the pre selected power factor angle ϕ

This method of control has advantage that the harmonics of converter input voltage v_i and consequently the harmonic currents at converter input occur at the well defined frequencies Therefore the filters can be designed to suppress the *ac* current harmonics However this method of control is sensitive to the changes in values of supply parameters and is slow in response [19]

3.4 Principle of Converter Control :

Figs 3 5, 3 6 and 3 7 gives the principle o PWM control The triangular carrier wave of given frequency is compared with the sinusoidal modulating wave of supply frequency The switching signals for the devices S1 to S4 of the converter are generated by the intersection of sine and triangular waves

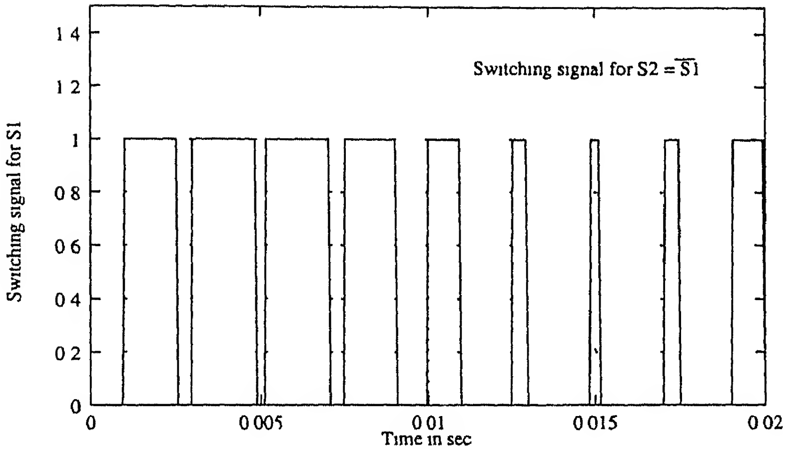


Figure 3 6 Switching signals to switches S1 and S2

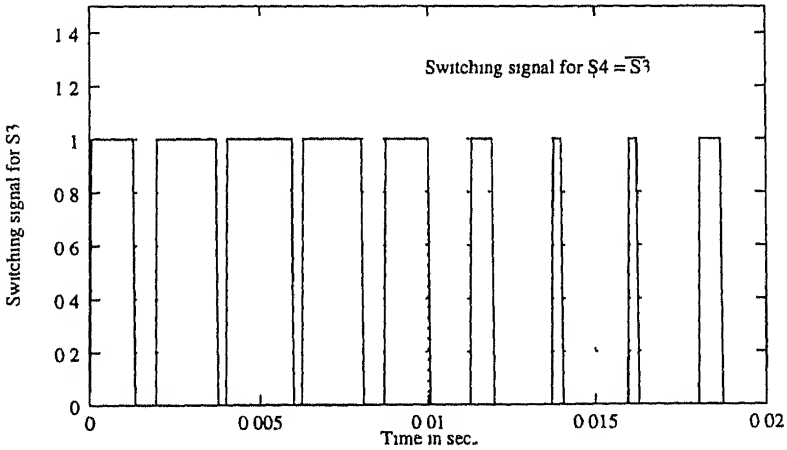


Figure 3 7 Switching signal to switches S3 and S4

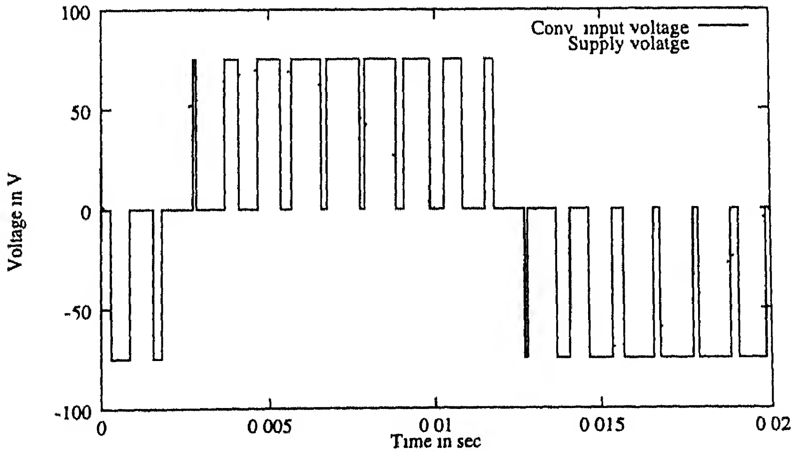


Figure 3 8 The voltage waveform at the converter input terminals for forward power flow

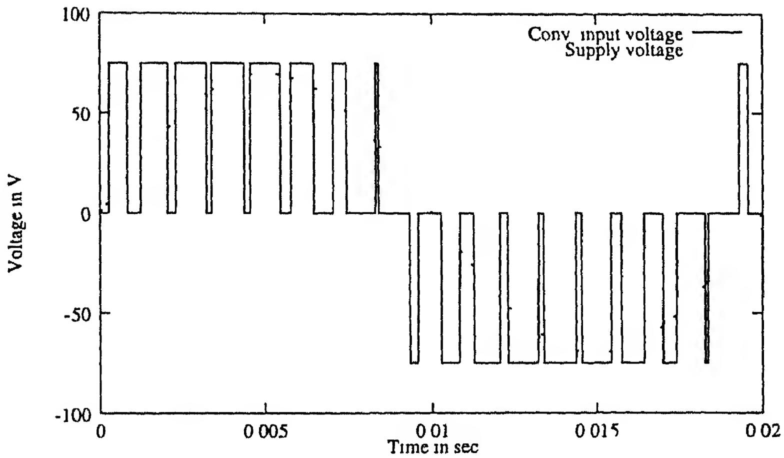


Figure 3 9 The voltage waveform at the converter input terminals for the reverse power flow

Figs 3 8 and 3 9 shows the input voltage V_i obtained at the converter input terminals, by PWM control of the *dc* link voltage V_d The magnitude of converter input voltage V_i is controlled by varying the modulation index, and the phase of converter input voltage V_i is controlled by varying the phase of modulating voltage w r t the supply voltage

Fig 3 8 shows the converter input voltage for forward power flow, while fig 3 9 shows the converter input voltage for reverse power flow

In the case of Electric Traction, the switching signals are generated by a microcontroller For such a system, the switching signals for the devices S1 to S4 are generated by the method of sampled asymmetric pulse width modulation techneque Fig 3 10 shows the principle of such a control In this method, the amplitude of the modulating signal is sampled at the positive or negative peak of carrier wave is held constant until the next sampled interval The point of intersection of the sampled value with the rising / falling triangular wave gives the switching instant [20] With this method it is easy to calculate the switching instants by a simple trigonometric function as given by the following equations

Assuming that the peak of triangular carrier wave is synchronized with the zero of supply voltage we have -

$$\alpha_{2i-1} = \frac{\pi}{2R}\left[4i - 3 - M_f sin(\frac{\pi(2i-2)}{R})\right] \qquad (3\ 20)$$

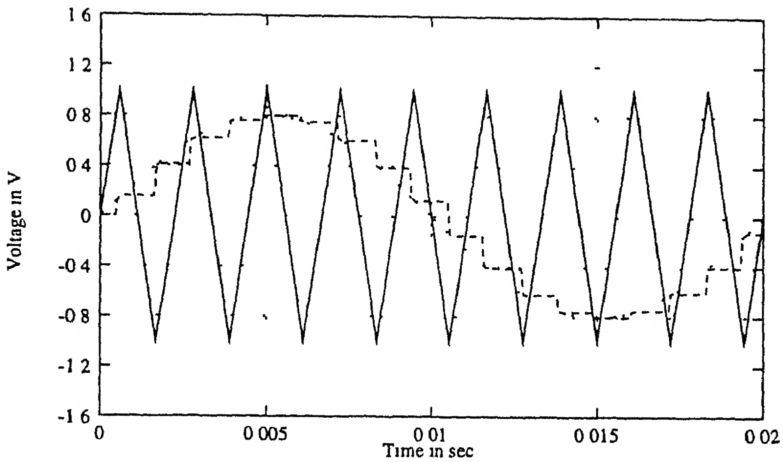


Figure 3 10 Principle of the converter control with regular sampled asymmetric pulsewidth modulation method

$$\alpha_{2i} = \frac{\pi}{2R}\left[4i - 1 - M_f sin(\frac{\pi(2i-1)}{R})\right] \tag{3 21}$$

$$R = \frac{f_c}{f_s} \tag{3 22}$$

Where,

i = 1,2,3,4 switching instant

M_f = modulation index

R = frequency ratio

f_S = supply frequency

f_c = carrier frequency

The microprocessor can be programmed suitably and hence the switching instants can be generated on line by the processor using the above equations

3.5 Design Criteria for Synchronous Link Converter :

For the proper operation of a Synchronous Link Converter the following factors have to be considered

3.5.1 Loss of Control Limit :

The anti parallel diodes have to be normally reverse biased This condition ensures that switching of the devices can control the waveform of *ac* input current This requires that the *dc* link voltage V_d to be always greater than the peak of *ac* voltage [21]

i e

$$V_d \geq \sqrt{2}\ \ V_s \tag{3 23}$$

3.5.2 Maximum Operating Range :

The Synchronous Link Converter has the constant output voltage and the output voltage is independent of the input voltage Also the output voltage is higher than the peak of supply voltage, so that the anti parallel diodes across the switches are all reverse biased Hence for the proper operation of synchronous link converter, there is a restriction on the output voltage given by following equations

For unity power factor operation we have -

$$V_{i1} = \sqrt{V_s^2 + (I_{s1}X_s)^2} \tag{3 24}$$

$$V_{i1} = \frac{M_f V_d}{\sqrt{2}} \tag{3 25}$$

for pulse width modulation with unipolar switching

Substituting equation 3 25 in equation 3 24 and solving for I_{s1} for $M_f = 1$ we get

$$I_{s1b} = \sqrt{\frac{0\ 5V_d^2 - V_s^2}{X_s}} \tag{3 26}$$

Where I_{s1b} is the maximum permissible rms input current (also known as current distortion limit [22]) for given value of *dc* link voltage V_d, supply voltage V_s and synchronous link inductor L_s

Fig 3 11 and fig 3 12 gives the allowable operating region of a Synchronous Link Converter without crossing current distortion limit for forward power transfer It is evident, the operating region of a Synchronous Link Converter is higher with the lower value of synchronous link inductor and the higher value of *dc* link voltage

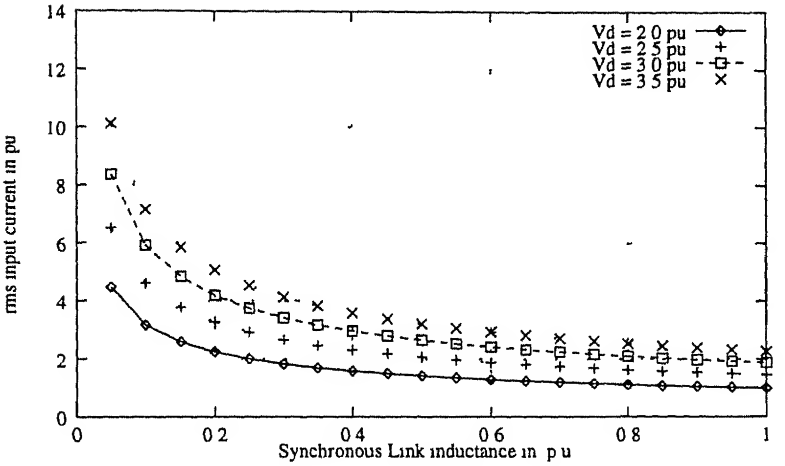


Figure 3 11 Maximum allowable rms input current as a function of synchronous link inductor

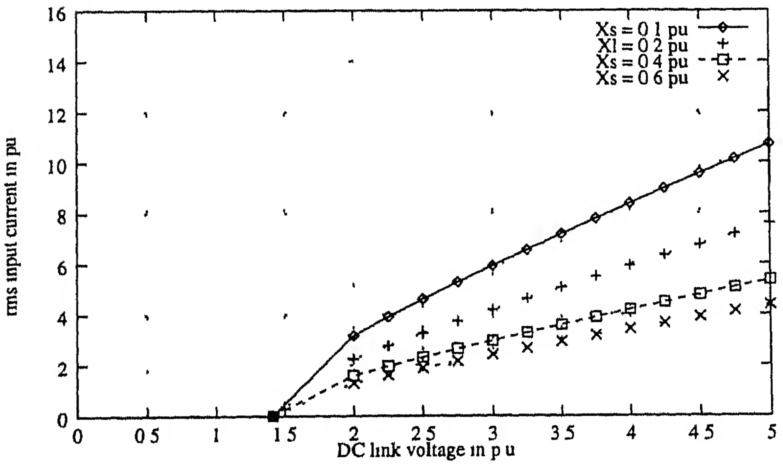


Figure 3 12 Maximum allowable rms input current as a function of *dc* link voltage

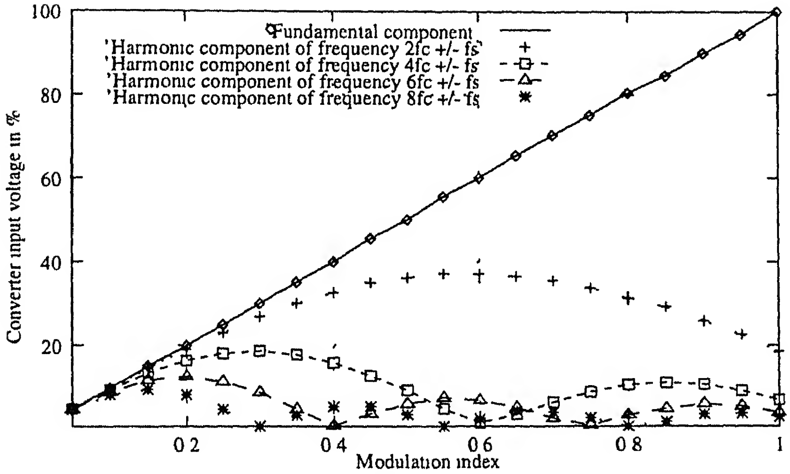


Figure 3 13 Calculated input harmonic voltage of a Synchronous link converter

3.5.3 Selection of ranges of modulation index :

The supply side harmonics of a synchronous link converter are a function of modulation index In order to get the input voltage harmonic characteristics of the converter the simulations were made, by assuming a constant *dc* link voltage The modulation index was varied from a minimum value (M_{fmin} of 0 05 has been used in the simulation) to the maximum value The switching devices were considered ideal The carrier frequency of 450 0 hz has been used in the simulation for getting the switching signal for switches The results of the simulation are given in the fig 3 13

Fig 3 13 shows the calculated harmonic voltages expressed as a percentage of the fundamental component of converter input voltage when modulation index is unity Fig 3 13 suggests, that for a single phase Synchronous Link Converter, the dominant harmonic frequencies in the order of amplitude are $2f_c \pm f_s$, $4f_c \pm f_s$, $6f_c \pm f_s$, $8f_c \pm f_s$ etc

Fig 3 14 shows the total harmonic voltage distortion at the converter input terminal as a function of modulation index Fig 3 15 shows the total harmonic current distortion at the converter input terminals (calculated using typical synchronous link inductance of 29 0 m H) as a function of modulation index

These characteristics suggests that for keeping the supply current harmonics low, the minimum value of modulation index should be kept above 0 7 for a single phase Synchronous Link Converter

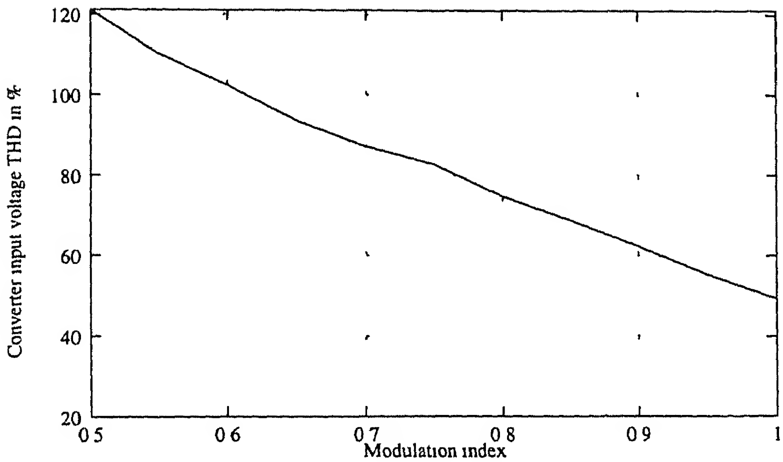


Figure 3 14 Total harmonic voltage distortion

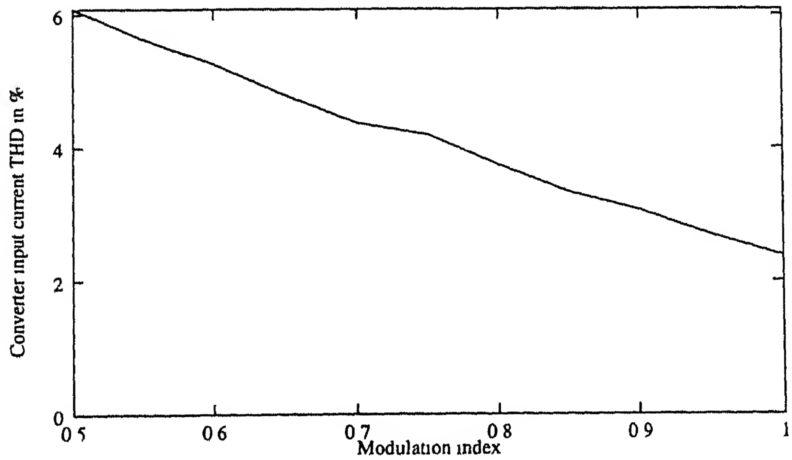


Figure 3 15 Total harmonic current distortion

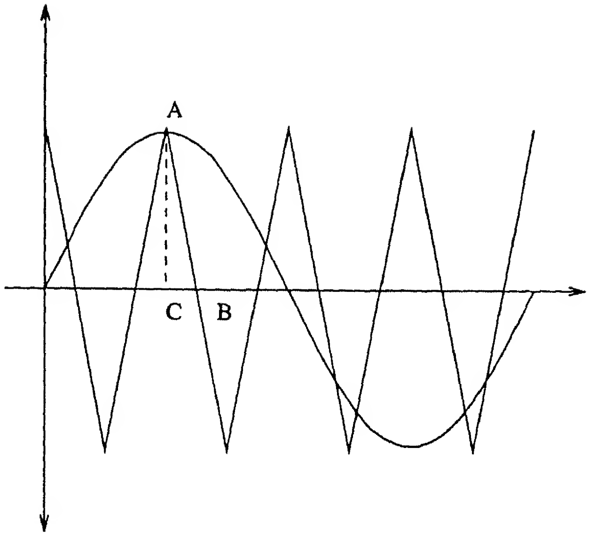


Figure 3 16 Principle of M_f calculation

Theoretically the maximum modulation index of the converter can be unity, but practically the maximum modulation index is decided by the turn off time of devices used, and the snubber relaxation time

When the switching signals are generated by comparison triangular wave and sinusoidal modulating wave, the maximum modulation index in terms of turn off time can be obtained as follows

Turn off time will be minimum when the peak of triangular wave coincide with the peak of the modulating sine wave

Let T_c be the time period of carrier wave and T_{off} be the turn off time of devices used

With reference to fig 3 16, consider Δ A B C we have

$$BC = \frac{T_c}{4} \tag{3 27}$$

When modulation index = 1 0 then $T_{off} = 0$ sec
When modulation index = 0 0 then $T_{off} = \frac{T_c}{2}$ sec

The relationship between T_{off} Vs modulation index is plotted in fig 3 17
Let the maximum modulation index = M_{fmax}
and the corresponding $T_{off} = T_{offmin}$

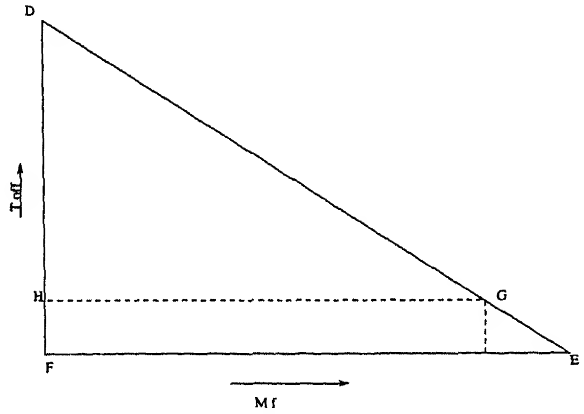


Figure 3 17 Relation between T_{off} and modulation index

From fig 3 17 we have

$$\frac{1}{\frac{T_c}{2}} = \frac{M_{fmax}}{\frac{T_c}{2} - T_{offmin}} \tag{3 28}$$

solving we get,

$$M_{fmax} = (1 - 2f_cT_{offmin}) \tag{3 29}$$

In the case of Electric Traction, where owing to higher power level the GTO thyristors are used in the construction of Synchronous Link Converter, the switching frequency used is low and around 450 hz Hence it is essential to synchronize the triangular carrier wave with the supply voltage In order to achieve the maximum modulation index, with given turn off time, it is essential to use the triangular carrier wave whose frequency is odd integer multiple of the supply frequency and with the peak of carrier wave synchronized with the zero of supply voltage With this positive peak of the modulating wave coincides with negative peak of the carrier wave and vice versa The frequencies that generally used are 350 hz, 450 hz and 550 hz

3.5.4 Selection of DC link Voltage :

Generally the Synchronous Link Converter is used as front end converter in the *ac* regenerative variable speed drives Hence the *dc* link voltage is decided by the line to line voltage rating of the motor

3.5.5 Selection of Synchronous Link Inductor :

For deciding the value of synchronous link inductor, the following factors are to be considered

1 For proper operation of the synchronous link converter, it is essential that the maximum modulation index at which the converter operates is close to unity, as permitted by the turn off time of devices used Under such conditions, the magnitude of converter input voltage V_{i1} varies over wide range, with the change in power demand on the converter This will ensure that the control will be less sensitive to errors Assuming that the converter operates with unity power factor, we can obtain expression for the modulation index as given by the following equation

$$M_f = \frac{\sqrt{V_s^2 + (I_{s1}X_s)^2}}{\frac{V_d}{\sqrt{2}}} \tag{3 30}$$

The equation 3 30 suggests that if a very low value of synchronous link inductor is used, the range of variation of modulation index (M_f) and hence converter input voltage V_{i1} becomes very much limited (with the change in load on the converter) and hence control becomes sensitive to errors

For maximum allowable modulation index, the maximum limiting value of the synchronous link inductor can be obtained as follows

From fig 3 3 we have

$$V_{s1} = V_{i1} cos\delta \tag{3 31}$$

$$I_{s1} = \frac{V_s - Vi1}{X_s} \tag{3 32}$$

$$P_{in} = \frac{V_s Vi1 sin\delta}{X_s} \tag{3 33}$$

$$P_{out} = V_d I_d \tag{3 34}$$

For a lossless converter we have, $P_{in} = P_{out}$

$$\frac{V_s V_{i1} sin\delta}{X_s} = V_d I_d \quad (3\ 35)$$

From equation 3 35 solving for L_s we get,

$$L_s = \frac{V_{i1} V_s sin\delta}{\omega V_d I_d} \quad (3\ 36)$$

For a given dc link voltage the maximum input voltage is given by -

$$V_{i1max} = \frac{M_{fmax} V_d}{\sqrt{2}} \quad (3\ 37)$$

Where,

M_{fmax} = the maximum modulation index as decided by turn off time of the devices used

$$\delta_{max} = cos^{-1}\left(\frac{V_s}{V_{i1max}}\right) \quad (3\ 38)$$

Substituting the equation 3 38 in equation 3 36 we get

$$L_{max} = \frac{V_s V_{i1} sin\delta_{max}}{\omega V_d I_{dmax}} \quad (3\ 39)$$

Where I_{dmax} = maximum value of the dc link current

2 As discussed in section 3 5 3, the dominant harmonics in the input voltage of synchronous link converter under consideration, around frequency that is at two times the switching frequency. The synchronous link inductor should be designed to keep the ripple in the input current at this frequency around certain percent of the maximum input current

The conservative value of the synchronous link inductor to keep the ripple in input current within this limit can be obtained as follows

Assuming the harmonic having same frequency as the switching frequency of converter will have approximately the same magnitude as the fundamental component of input voltage

$$V_{is} = \frac{4V_d}{\sqrt{2}\pi} \quad (3\ 40)$$

The value of the synchronous link reactance at effective switching frequency $= 2\pi f_{sw} L_s$

$$I_{is} = \frac{\frac{4V_d}{\sqrt{2}\pi}}{2\pi f_{sw} L_s} \tag{3 41}$$

Where,

V_{is} = rms harmonic voltage of the switching frequency

I_{is} = rms harmonic current of the switching frequency

f_{sw} = effective switching frequency

assuming I_{is} is limited to x% of I_{s1} we get

$$L_s = \frac{400\ 0V_d}{\sqrt{2}\pi(2\pi f_{sw})I_{s1}x} \tag{3 42}$$

Where $L_s \leq L_{max}$

The rms current rating of the inductor can be obtained as follows Assuming a loss free converter we have

$$V_s I_{s1} cos\phi = V_d I_d \tag{3 43}$$

$$I_{s1} = \frac{V_d I_d}{V_s cos\phi} \tag{3 44}$$

Generally $cos\phi = 1\ 0$ for the converter designed for industrial drive applications and in the case of Electric Traction applications

The actual I_{rms} can be considered to be 1 05 times the calculated I_{rms} to account for harmonic currents, power losses etc Also since the synchronous link inductor is on ac side and the ripple current is low, the inductor can be designed with iron core However increase in the core loss due to high frequency ripple current must be taken into account

3.5.6 Selection of Output Filter Capacitor :

The main criterion for selecting dc link capacitor C_d is based on the allowable ripple in dc link voltage It is usual to limit the ripple voltage due to second harmonic

currents within 5% of the rated value of dc link voltage As the output of the dc link is fed to an inverter, effective measures have to be taken to limit the effect of the second harmonic component Generally tuned filters are used to attenuate the second harmonic current in the dc link The value of dc link capacitor can be obtained as follows

Instantaneous power input to converter =

$$P_{in}(t) = \sqrt{2}V_s sin(\omega t) \times \sqrt{2}I_{s1} sin(\omega t) \tag{3 45}$$

$$P_{in}(t) = \sqrt{2}V_s \times \sqrt{2}I_{s1} \frac{(1 - cos2\omega t)}{2} \tag{3 46}$$

Instantaneous power output from the converter =

$$P_{out}(t) = V_d i_d(t) \tag{3 47}$$

$$i_d(t) = i_c(t) + I_l \tag{3 48}$$

Where,

$i_d(t)$ = instantaneous dc link current

I_l = load current

For a lossless converter

$$P_{in}(t) = P_{out}(t) \tag{3 49}$$

Solving equation 3 49 we get

$$i_d(t) = \frac{V_s I_{s1}}{V_d} - \frac{V_s I_{s1} cos(2\omega t)}{V_d} \tag{3 50}$$

Comparing equations 3 48 and 3 50 we get

$$I_d = I_l = \frac{V_s I_{s1}}{V_d} \tag{3 51}$$

$$i_c(t) = -I_d cos(2\omega t) \tag{3 52}$$

Capacitor ripple voltage =

$$\Delta V_d = \frac{1}{C_d} \int i_c(t) dt = \frac{I_d sin(2\omega t)}{2\omega C_d} \tag{3 53}$$

To restrict ΔV_d to x% of the *dc* link voltage V_d, the value of the capacitor should be

$$C_d \geq \frac{V_s I_{s1} 100}{2\omega {V_d}^2 x} \tag{3 54}$$

The rms current through the capacitor is given by

$$I_{crms} = \frac{I_d}{\sqrt{2}} = \frac{V_s I_{s1}}{V_d \sqrt{2}} \tag{3 55}$$

Hence the rms current rating of the capacitor have to be greater than I_{crms} as given by the equation 3 55

The *dc* voltage rating of the capacitor will depend upon the *dc* link voltage It is necessary to have a safety factor of 1 25 for the actual rated voltage of the capacitor, over actual *dc* link voltage to account for over charging during transients However this safety factor could be reviewed only after experience

3.5.7 Device rating :

(a) Forward Blocking voltage

The forward blocking voltage of the GTO / IGBT will be chosen by following condition -

When any of the switches conduct, the switch in same leg has to block the full *dc* link voltage V_d Hence the forward blocking voltage rating of the switch should be greater than the *dc* link voltage V_d Generally a margin of about 25% is to be given, after taking into consideration the *dc* link voltage and the voltage jump on account of the inductance and capacitance in circuit

(b) Forward $\frac{dv}{dt}$

Maximum forward dv/dt occurs at every turn on When switch S2 is off the diode D1 will be conducting. The voltage across switch S1 will be zero When the switch S2 is turned on, diode D1 turns off and a full *dc* link voltage appear across switch S1 The switch S1 has to block a forward voltage equal to V_d This change from zero to V_d occurs in a finite time depending on the turn on time characteristics of the device

In order to protect the device against high $\frac{dv}{dt}$, generally a snubber circuit is connected across the devices [23]

3.6 Design of a typical Single phase Synchronous Link Converter :

Design data :

1 Output dc power = P_d = 1 0 kW

2 Input supply voltage = V_s = 1 ϕ, 110 V, 50 Hz

3 Output dc Voltage = V_d = 220 0 V

4 Output voltage rιpple = 5 0 % of V_d

5 Input current rιpple = 3 0 % of the rated rms value of the ιnductor current

6 Carrιer Frequency = 2000 0 hz

Followιng the desιgn procedure gιven ιn sectιon 3 5, the ratιngs of varιous components evaluated are gιven below

1 Maxιmum value modulatιon ιndex = 0 95 (assumed)

2 L_{max} = 34 5 mH

3 for lιmιtιng ιnput current rιpple to 3 % = L_s = 28 9 mH

4 rms current ratιng of the ιnductor = 9 6 A

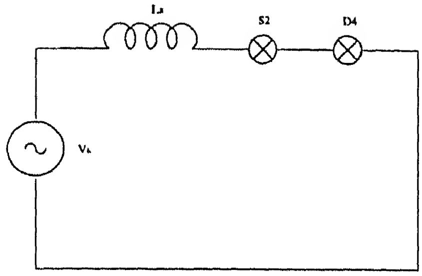
5 Output capacιtor to keep rιpple ιn voltage wιthιn 5 % $\geq$ 1320 0 μF

6 Current ratιng of the output filter capacιtor $\geq$ 3 2 A

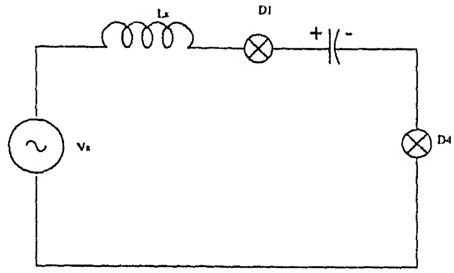
7 Voltage ratιng of the output filter capacιtor $\geq$ 275 0 V

3.7 Digital Simulation :

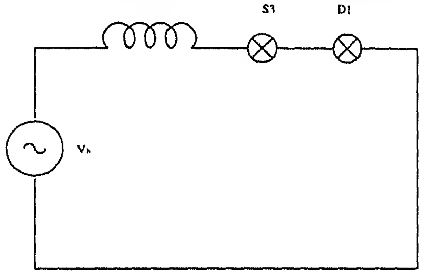
Fιg 3 18 shows dιfferent states, ιn the operatιon of Synchronous Lιnk Converter, durιng the posιtιve half cycle of supply voltage, under forward



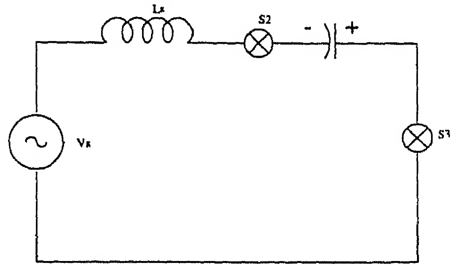
(a) When switch S2 and S4 conducts



(b) When switch S1 and S4 conducts

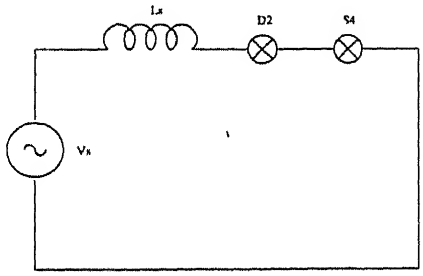


(c) When switch S1 and S3 conducts

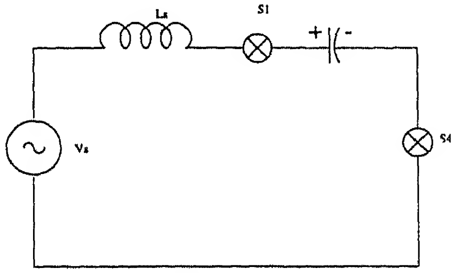


(d) When switch S2 and S3 conducts

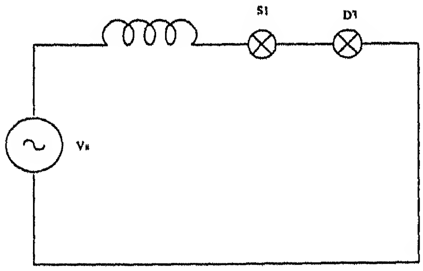
Figure 3 18 Different states in the operation of Synchronous Link converter (for forward power flow condition)



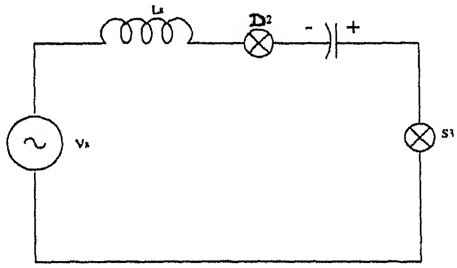
(a) When switch S2 and S4 conducts



(b) When switch S1 and S4 conducts



(c) When switch S1 and S3 conducts



(d) When switch S2 and S3 conducts

Figure 3 19 Different states in the operation of Synchronous Link converter (for reverse power flow condition)

In fig 3 18 when the switch S2 is closed, supply source is shorted through the synchronous link inductor, switch S2 and diode D4 The application of Kirchoff's voltage law around the close loop we get

$$V_s = L_s \frac{di_s}{dt} + Ri_s \tag{3 56}$$

$$or \quad \frac{di_s}{dt} = \frac{V_s - Ri_s}{L_s} \tag{3 57}$$

The equation 3 57 suggests that the slope is positive Hence the current rises during this interval During this state the energy is stored in the synchronous link inductor, and the output capacitor feeds the load

$$\frac{dV_d}{dt} = - \frac{I_l}{C_d} \tag{3 58}$$

In fig 3 58b when the switch S2 is turned off the diodes D1 and D2 conduct By application of Kirchoff's voltage law around a close loop we get

$$V_s = L_s \frac{di}{dt} + V_d + Ri_s \tag{3 59}$$

$$\frac{di}{dt} = \frac{(V_s - V_d - Ri_s)}{L_s} \tag{3 60}$$

$$\frac{dV_d}{dt} = \left[\frac{i_s}{C_d} - \frac{I_l}{C_d}\right] \tag{3 61}$$

The equation 3 60 suggests that the slope is negative Hence the current falls during this interval and the stored energy in the synchronous link inductor is transferred to the output capacitor and load circuit

Fig 3 19 shows different states, in the operation of Synchronous Link Converter, during the positive half cycle of supply voltage, under reverse power flow

In general these equations can be written in matrix form as follows ,

$$\frac{d}{dt}\begin{bmatrix} i_s \\ V_d \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_s} & -\frac{p}{L_s} \\ \frac{p}{C_d} & 0 \end{bmatrix}\begin{bmatrix} i_s \\ v_d \end{bmatrix} + \begin{bmatrix} \frac{V_s}{L_s} \\ -\frac{I_l}{C_d} \end{bmatrix} \tag{3 62}$$

Where,

p is the switching function

$p = 1$ if S1 and S4 conduct

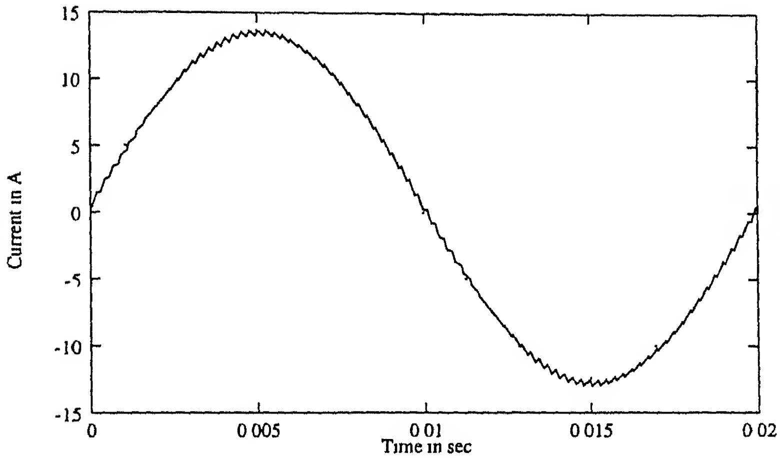


Figure 3 20 Supply current waveform (forward power flow)

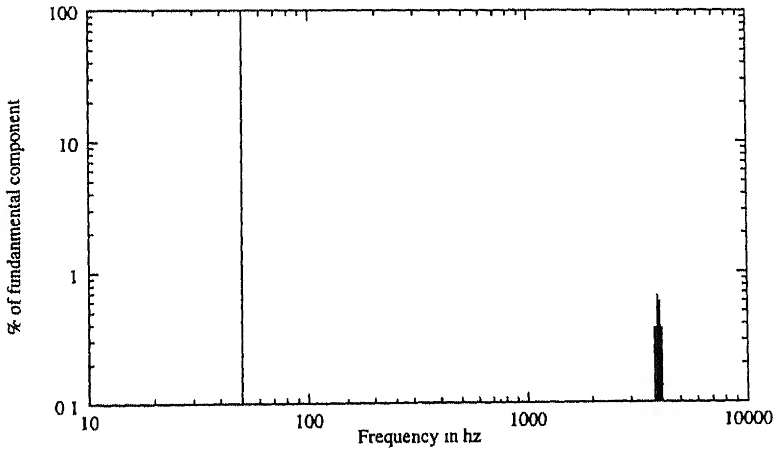


Figure 3.21 Supply Current Harmonic Spectrum (forward power flow)

$p = -1$ if S2 and S3 conduct

$p = 0$ if S2, S4 or S1, S3 conduct

The equation 3 62 is solved iteratively to obtain the steady state analysis of the converter. A dedicated computer program was developed for the purpose The design data of section 3 6 was used in the simulation

The simulated input current wave form, converter input voltage waveform, *dc* link voltage waveform, under rated load conditions are shown in figs 3 20, 3 22 and 3 23 The switching frequency used in simulation was 2000 hz The harmonic spectrum of line current is shown in fig 3 21 The dominant component as expected appear at frequency around 4000 hz The fundamental component of the input

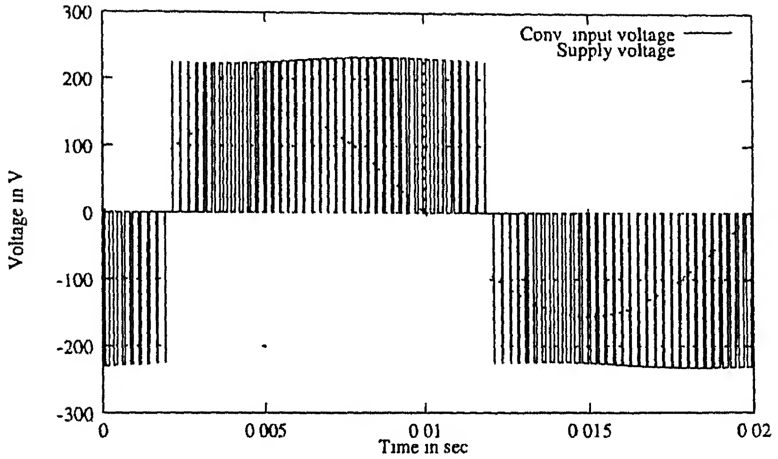


Figure 3 22 Converter input voltage waveform (forward power flow)

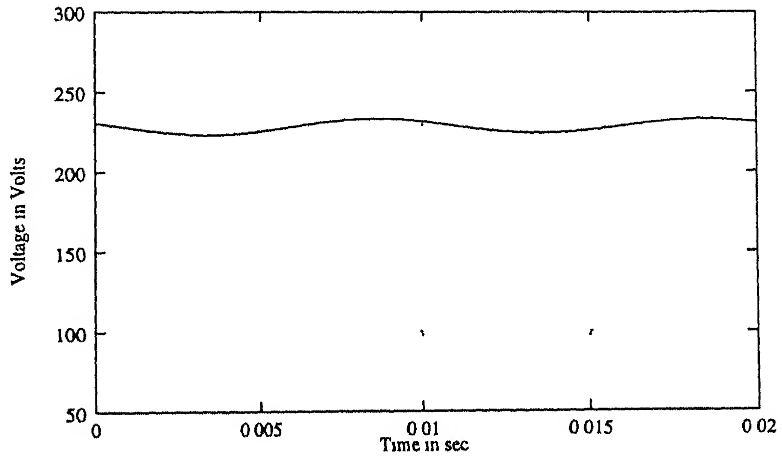


Figure 3 23: DC Link Voltage Waveform

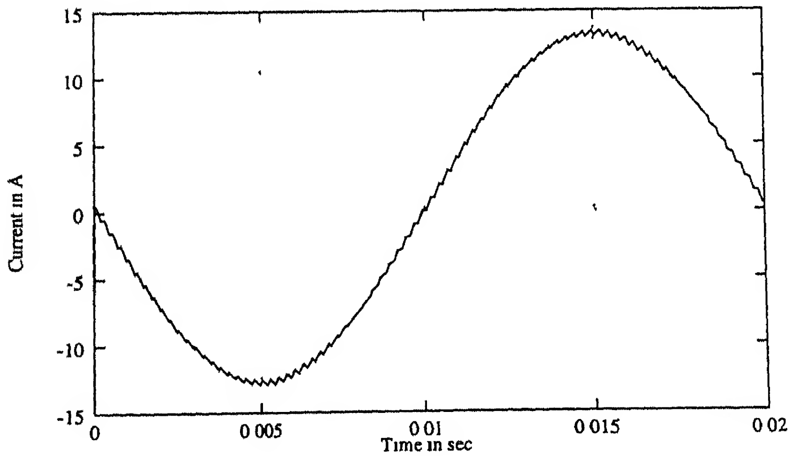


Figure 3 24· Supply current waveform (reverse power flow)

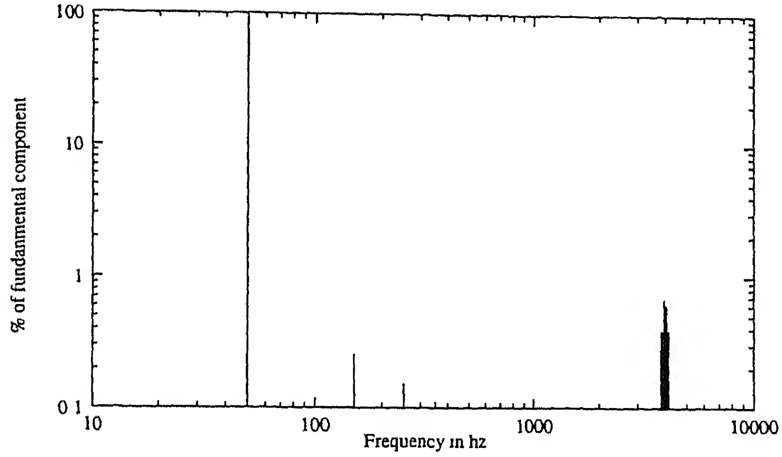


Figure 3 25 Supply Current Harmonic Spectrum (reverse power flow)

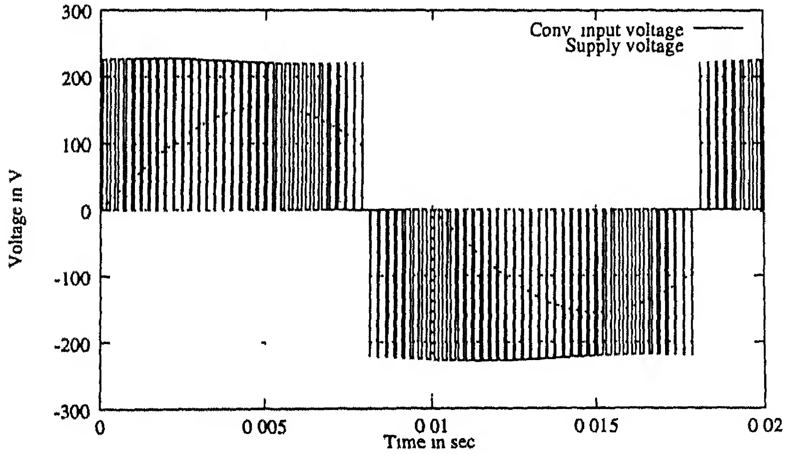


Figure 3 26 Converter input Voltage waveform (reverse power flow)

current is essentially in phase with the supply voltage

The simulated input current waveform, converter input voltage wave form for reverse power flow (regeneration) are shown in fig 3 24 and fig 3 26 The corresponding frequency spectrum of the input current is shown in fig 3 25

From these simulation we find that the characteristic of Synchronous Link Converter remains essentially same for either direction of power flow

3.8 Conclusion

Due to their simple construction, design, capability for bidirectional power flow, reduced input line current harmonics and unity power factor operation the Synchronous Link Converters are widely used as front end converters in regenerative ac drives When Synchronous Link Converters are used as front end converter in *ac* regenerative Traction Drives, due to their inherent ability to operate with reduced harmonic currents, the interference to telecommunication and track circuit reduces Further the unity power factor operation of the converter will results in higher efficiency

Chapter 4

Experimental Verification and Observation

4.1 Objective of Experiment :

The experimental verification was made to study the unity power factor operation of Synchronous Link Converter The experimental unit of Synchronous Link Converter was designed with the following specifications

1 Power rating of the Converter = 200 0 W

2 Supply voltage = 35 0 V, 1 ϕ, 50 hz

3 DC link Voltage = 75 0 V

4 Carrier frequency = 1000 0 hz

5 Dynamic variation of the *dc* link voltage = 5 0%

The Synchronous Link converter was realized using Insulated Gate Bipolar Transistor (IGBT) Hybrid IC driver circuit was used to get the required isolation between the control circuit and the power circuit and for getting the necessary drive power amplification The IC driver circuit has the features like over current detection, low speed over current cut off characteristics and the gate turn off power supply to make the fullest use the IGBT.

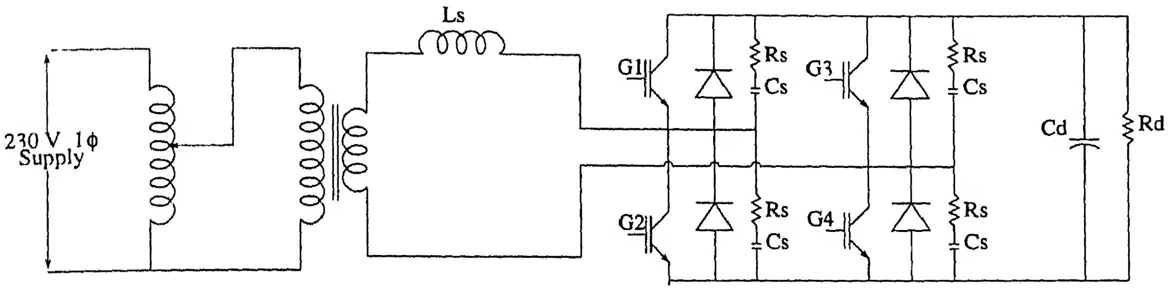


Figure 4 1 Experimental power circuit of the Synchronous Link Converter

4.2 Power Circuit :

Fig 4 1 shows the power circuit of Synchronous Link Converter used in the experimental set up Resistor R_d was used to represent the Inverter / Chopper load The following are the components used for realizing the power circuit

1 ID221KA2 Dual IGBTMOD Power module, 25 0 A, 1000 0 v, Make - Power Rex

2 0.1 μF, 22 0 Ω Snubber

3 3 8 mH Synchronous Link Inductor

4 230 0 / 50.0 V Step Down transformer

4.3 Control Circuit :

The control circuit generates the switching signal The control circuit incorporates, the modulation index control and the phase angle control which are essential in the operation of Synchronous Link Converter The control circuits has the following sub circuits

1. Reference Signal Generator

2 Lead / Lag reset Signal Generator

3 Line Synchronized Triangular Wave Generator

The specifications for various components used in the control circuit are given in Appendix II

4.3.1 Reference Signal Generator :

Fig 4 2 gives the circuit diagram of the reference signal generator The reference signal which is a sine wave is stored in an EPROM The sine wave is stored in location 0000 h to 03FF h of a Intel 2732 EPROM The ten least significant bits of the counter are used to address the locations of the EPROM For the operation of Synchronous Link Converter, it is essential that the frequency of the reference signal to be the same as that of supply frequency For this purpose a phase locked loop together with divide by 'N' counter is used for generating the necessary clock signal for counter When the counter is driven by the clock signal, it addresses the memory locations of the EPROM continuously and a sine wave is obtained at the output of the digital to analog converter DAC08 The frequency of sine wave is same as that of of the supply frequency This sine wave can be used for generating switching signal for the switches in one of the two legs the switching signal for the other leg is generated by the sine wave which is phase shifted by 'π' radians with reference to the first sine wave For varying the modulation index, magnitude of the reference sine wave is varied by varying the resistor $R13$ Fig 4 3 shows the reference signal wave form required for the IGBT's S1,S2 and S3,S4 of power circuit

4.3.2 Lead / Lag Reset Signal Generator :

Fig 4 4 gives the circuit diagram of Lead / Lag reset signal generator This circuit generates reset signal, for obtaining the necessary phase angle in the modulating signal. Fig 4 5 shows the waveforms obtained at various stages of the circuit The output of the zero crossing detector is processed by the positive edge triggered monostable multivibrator When the output of monostable multivibrator is at zero level, the transistor $T2$ remains in cutoff and capacitor '$C4$' of the integrator charges linearly from the supply voltage The output of positive edge triggered monostable multivibrator becomes high when the supply voltage passes through zero and goes negative This drives the transistor $T2$ into saturation, shorting the capacitor

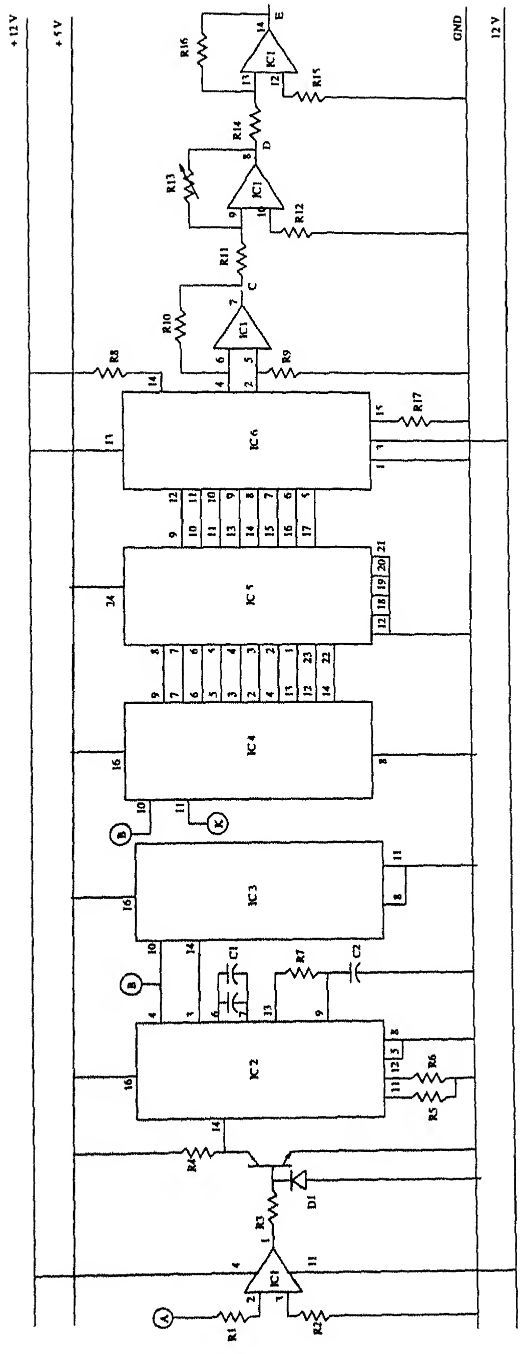


Figure 4 2· Reference signal generator circuit

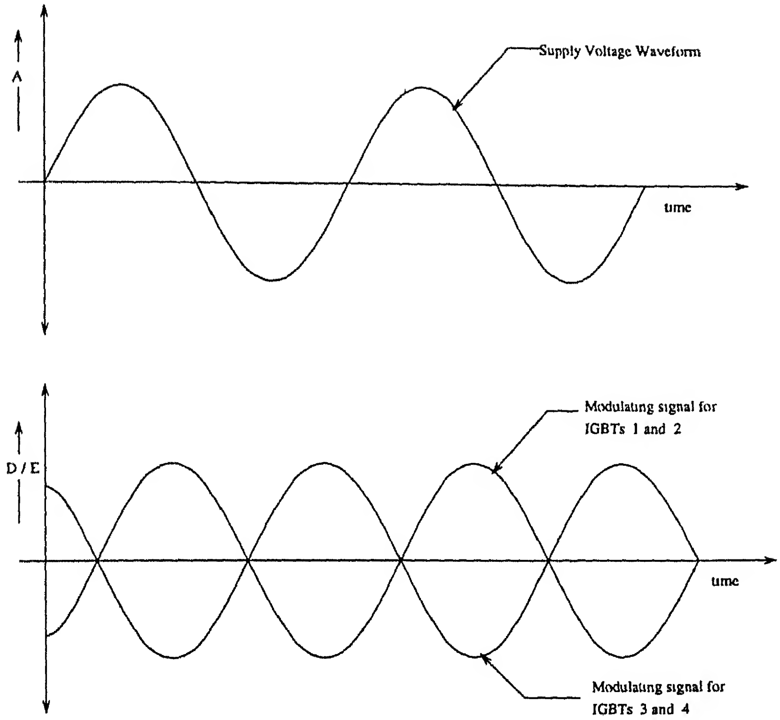


Figure 4 3 Reference signals for the IGBTs

The capacitor discharges to essentially zero voltage The resulting ramp signal is level shifted to remove the DC component, and compared with the voltage V_c in a comparator The magnitude of the voltage V_c can be adjusted depending on the phase angle requirement. The voltage V_c is positive for the forward power flow and is negative for the reverse power flow The output of comparator is processed by a positive edge triggered monostable multivibrator The output of monostable multivibrator is passed to a buffer stage to reduce the level of voltage These narrow pulses are used to reset the counter of reference signal generator circuit The counter gets reset once per cycle of the supply voltage, resulting in phase shifted reference sine wave at the output of reference signal generator circuit

4.3.3 Line Synchronized Triangular Wave Generator :

Fig 4 6 gives the circuit of Line Synchronized Triangular Wave Generator The line synchronization of triangular wave is essential to get equal number of switching pulses in a half cycle of supply voltage waveform It consists of a Voltage Controlled Oscillator (VCO), designed to give a square wave output of 1000 0 hz frequency.

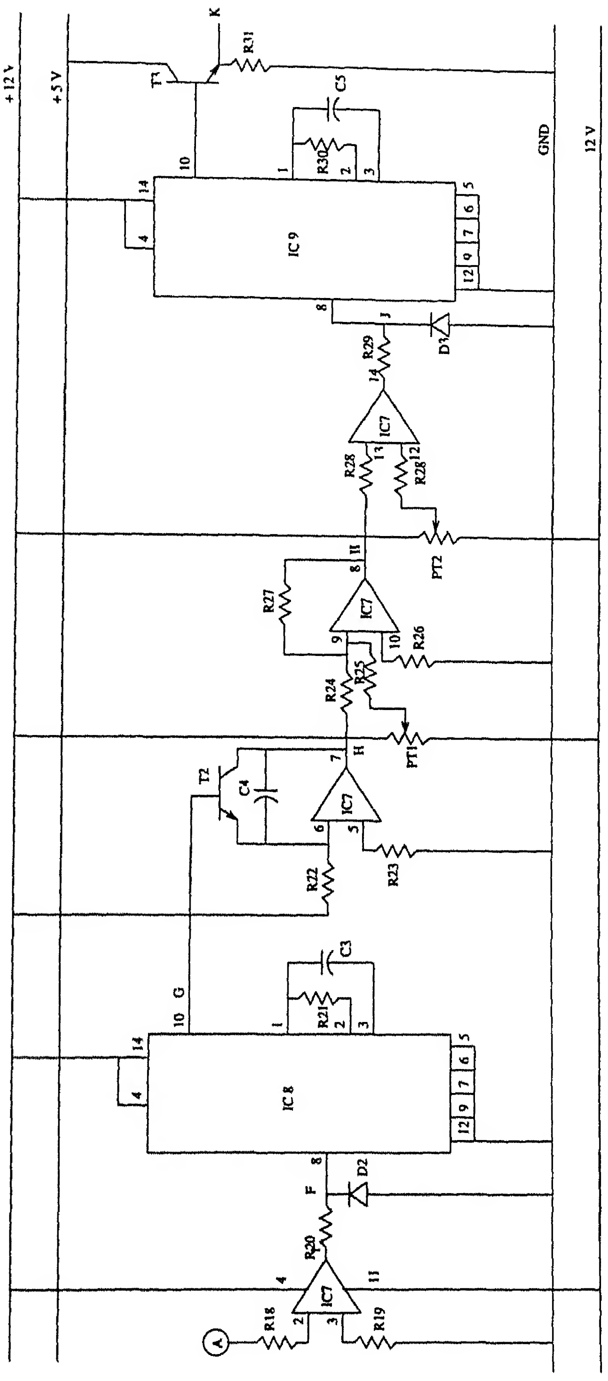


Figure 4 4 Lead / Lag reset signal generator circuit

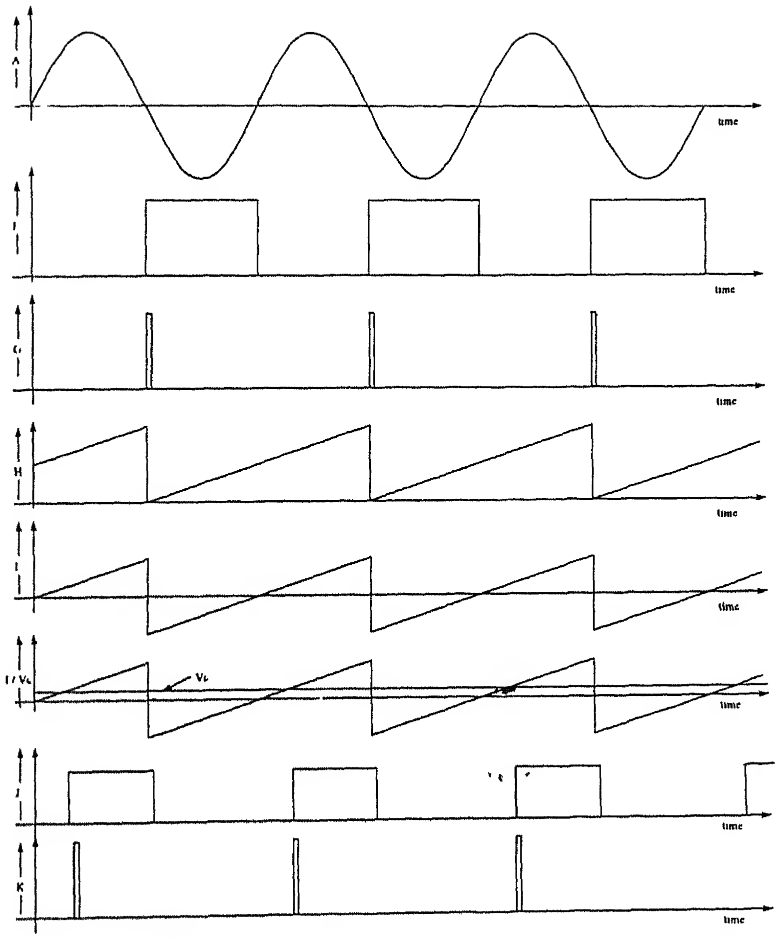


Figure 4 5 Waveforms at various stages of the Lead / Lag reset signal generator circuit

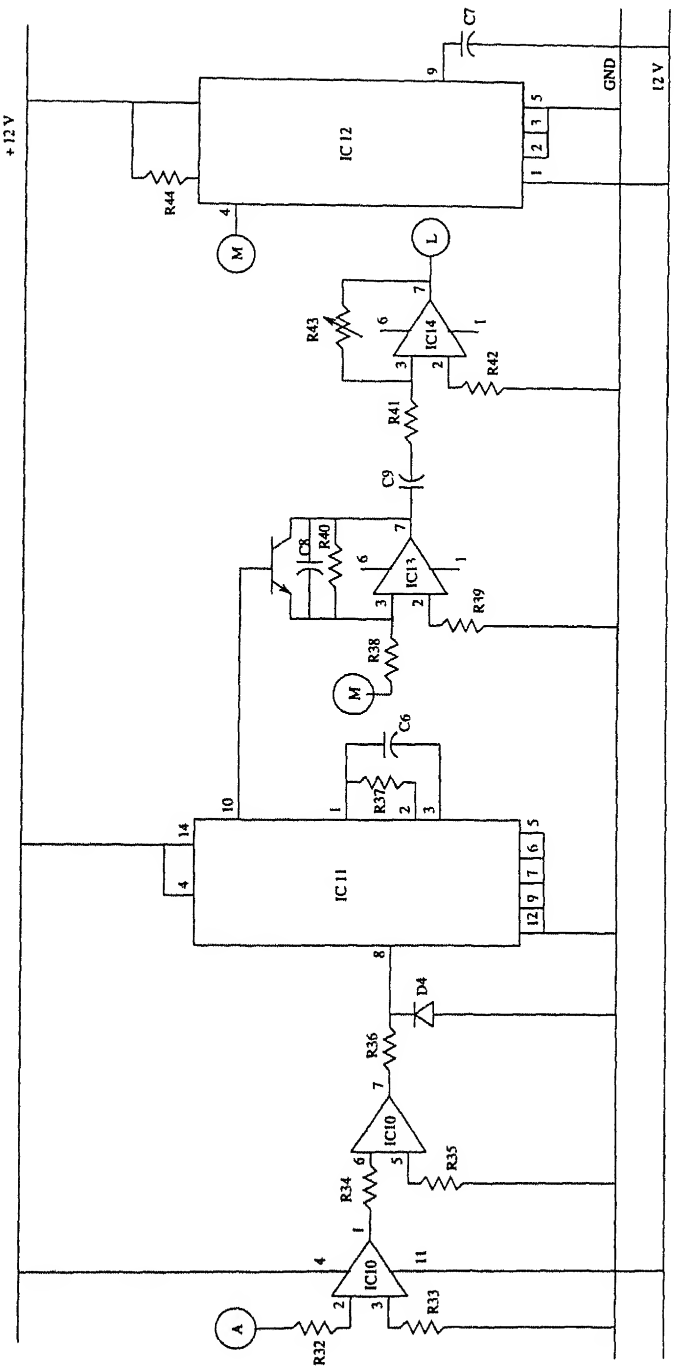


Figure 4 6 Line Synchronized Triangular Wave generator circuit

The output of VCO is fed into the integrator to get triangular wave For synchronizing the triangular wave with the supply voltage, capacitor $C8$ of the integrator is discharged every time when the supply voltage goes to zero and becomes positive This is done by driving transistor $T4$ into saturation, by the reset pulses generated by positive edge triggered monostable multivibrator The monostable multivibrator is driven by the zero crossing detector and the phase shifter circuits

4.3.4 Switching Signal Generator :

Fig 4 7 shows the Switching Signal Generator It basically consists of comparators to compare the sine and triangular waveforms The output of the comparator are processed by the blanking circuit The blanking circuit uses the comparator output and generates switching signals for the IGBT's in the same leg of Synchronous Link Converter The switching signals are generated in such manner, that the turn on of incoming switches are delayed by a small duration ($\leq 10\ \mu$ sec) to ensure the turn off of out going switches This prevents the shoot through fault in Synchronous Link Converter

4.4 Driver Circuit :

Fig 4 8 gives the circuit connections of IC driver circuit The driver circuit has following functions

1 Isolates the control circuit from the power circuit

2 Provides the protection against the over current based on the collector voltage sensing IGBT's cannot withstand an over current for more than 10 μ sec duration The IC driver provides extremely fast protection

3 Maintains the negative gate drive during turn off, for reducing the turn off time of the devices and for preventing the spurious turn on of device

The components specifications of driver circuit are given in Appendix II

Fig 4 9 shows the waveforms obtained at output of the IC driver during normal and faulty conditions

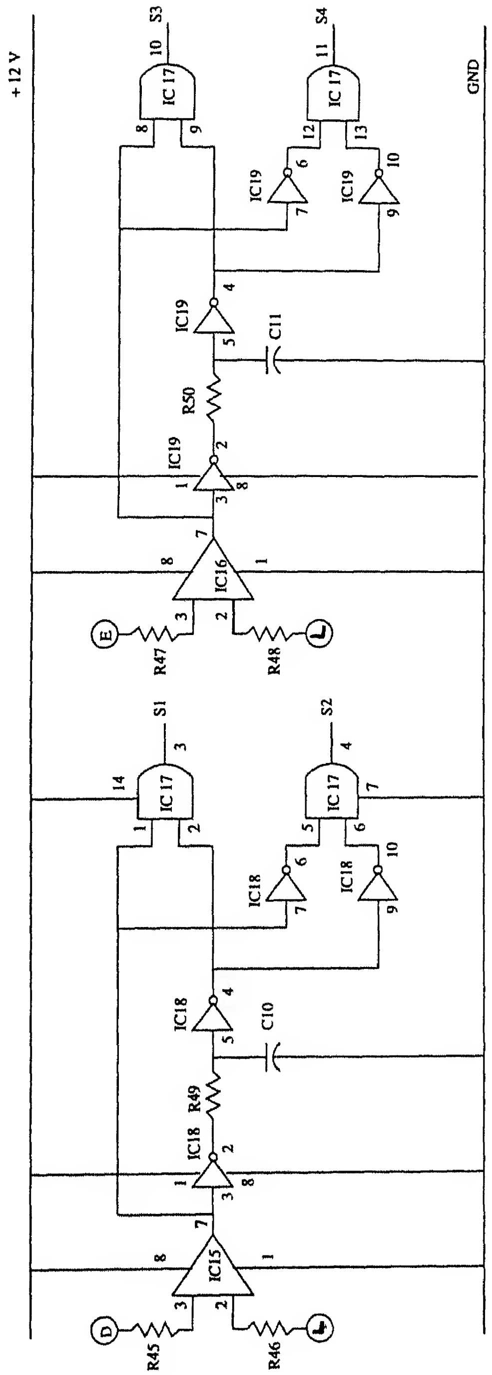


Figure 4 7 Switching Signal generator circuit

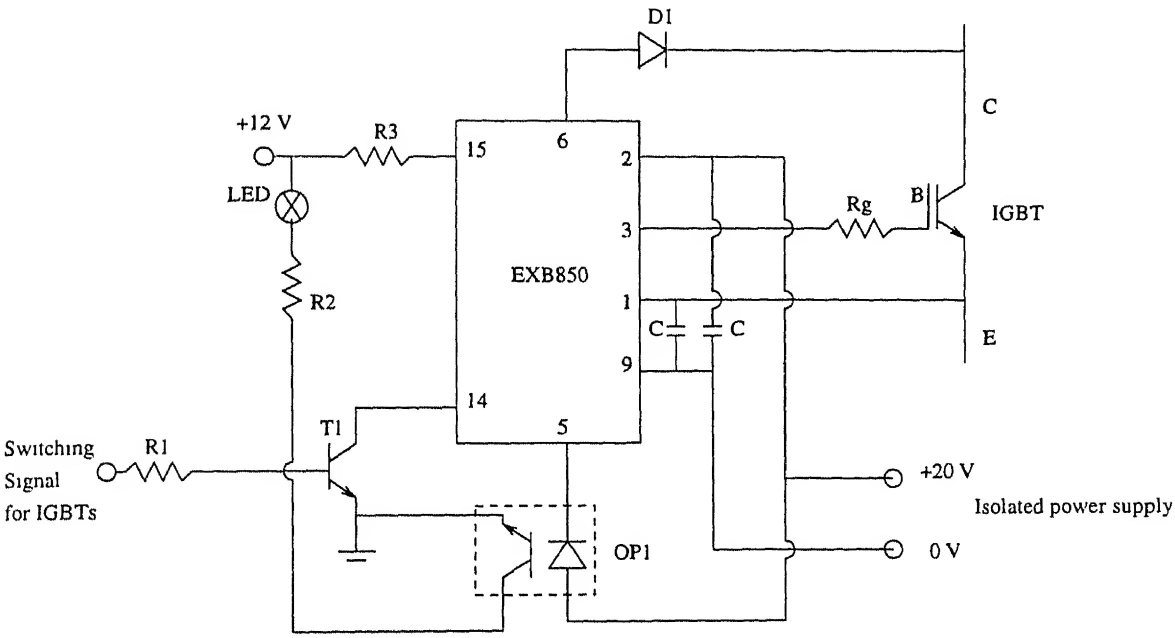


Figure 4 8 Driver circuit

4.5 Experimental Test Results :

The power circuit, the driver circuit and the control circuit are integrated and tested The circuit is started by applying a low voltage through a auto transformer This results in the charging of capacitor C_d through the single phase bridge rectifier formed through the anti parallel diodes of the IGBT's The switching signals for IGBT's are then given This results in the regular operation of Synchronous Link converter The input voltage is then adjusted to the required voltage through the auto transformer

The experimental waveforms of the control circuit are shown in the fig 4 10–fig 4 16 These waveforms are taken for the forward power flow at unity power factor operation The corresponding waveforms for the power circuit are given in the fig 4 17–fig 4 21 These waveforms are similar to those obtained through the digital simulations and indicates the operation of converter with nearly unity power factor

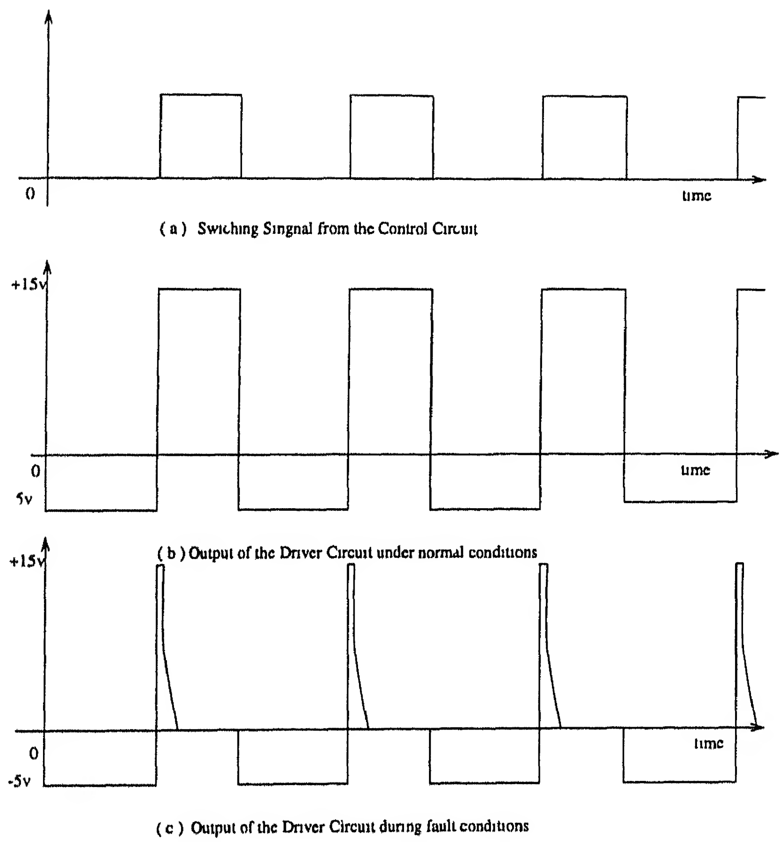


Figure 4.9 Driver circuit output

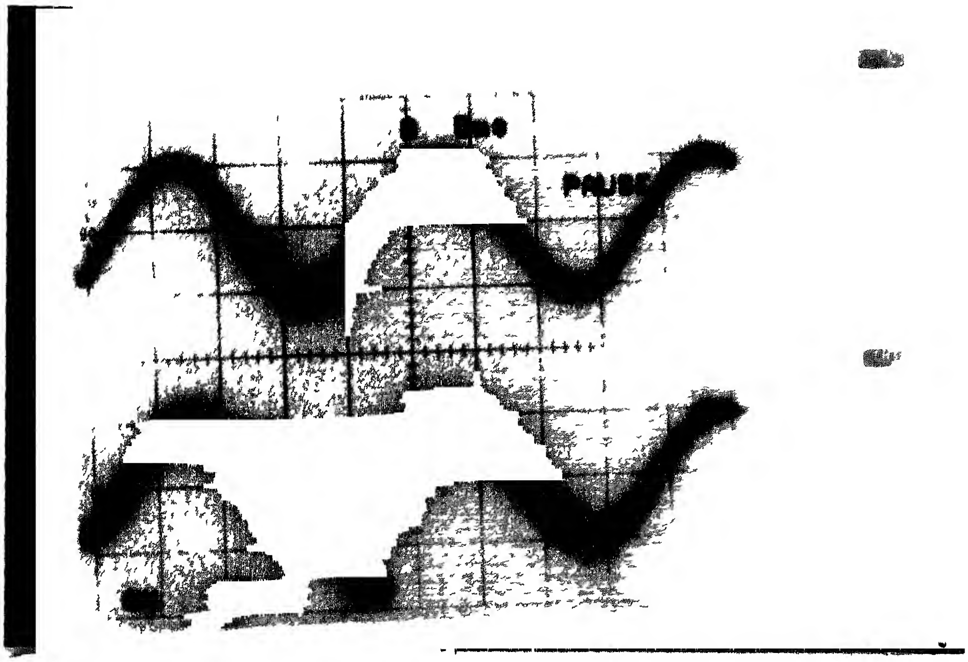


Figure 4 10 Supply Voltage waveform and Modulating Signal I

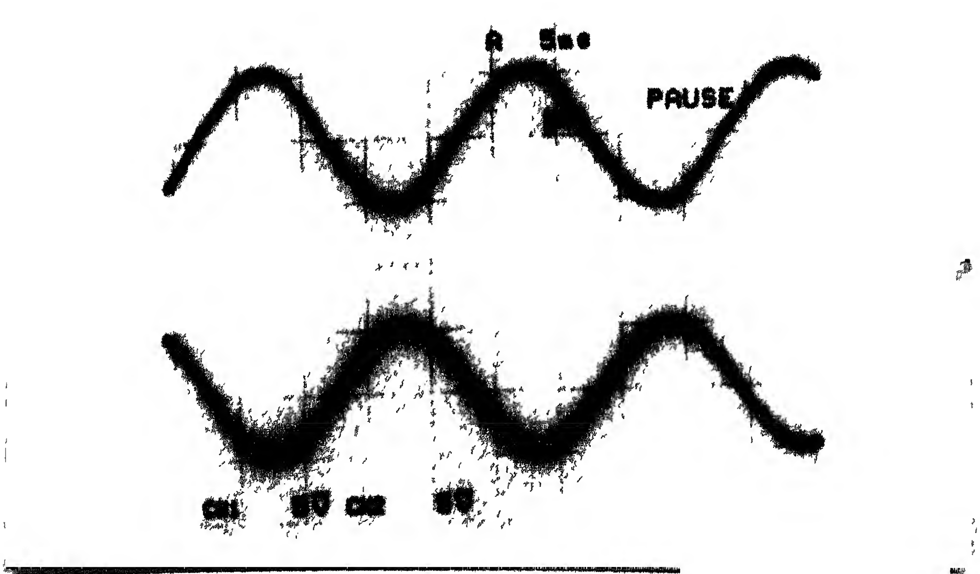


Figure 4 11 Supply Voltage waveform and Modulating Signal II

Figure 4 12 Line synchronization of the Carrier wave

Figure 4 13 Principle of switching signal generation for IGBT's in same leg

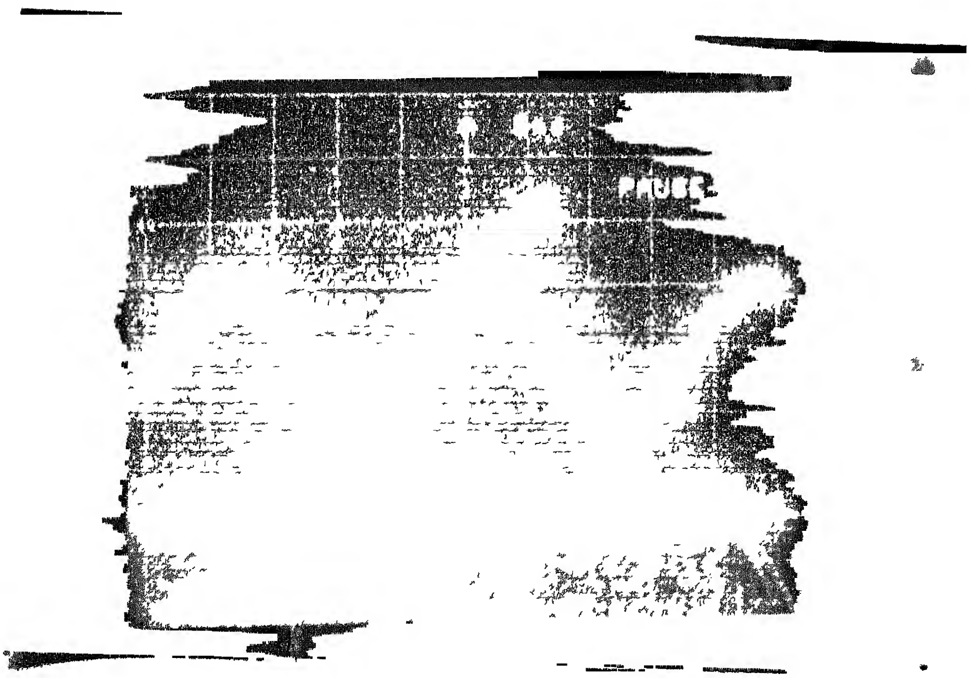


Figure 4 13 (a) Reset Signal for reference signal generator

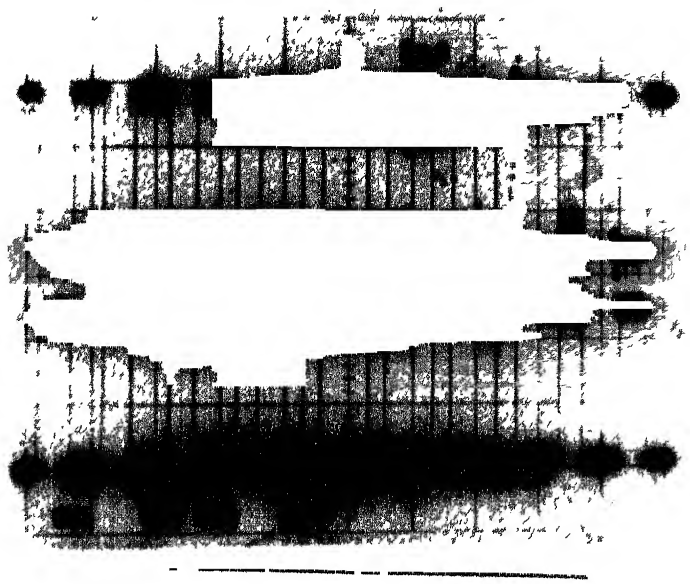


Figure 4 14 Switching signal for IGBT's 1 and 2

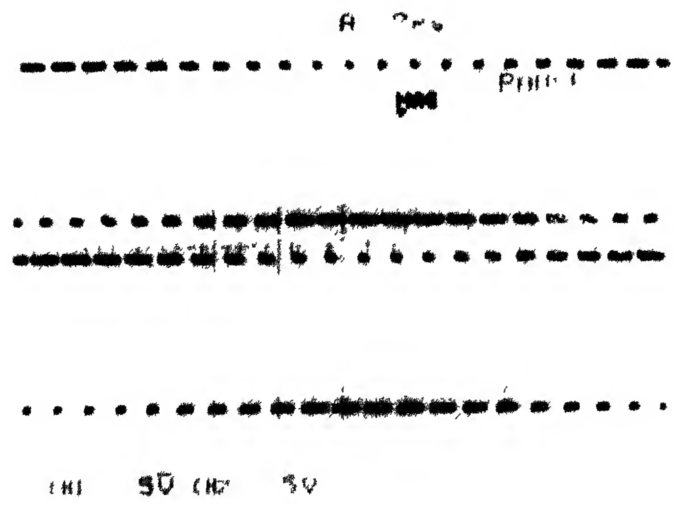


Figure 4 15. Switching signal for IGBT's 2 and 3

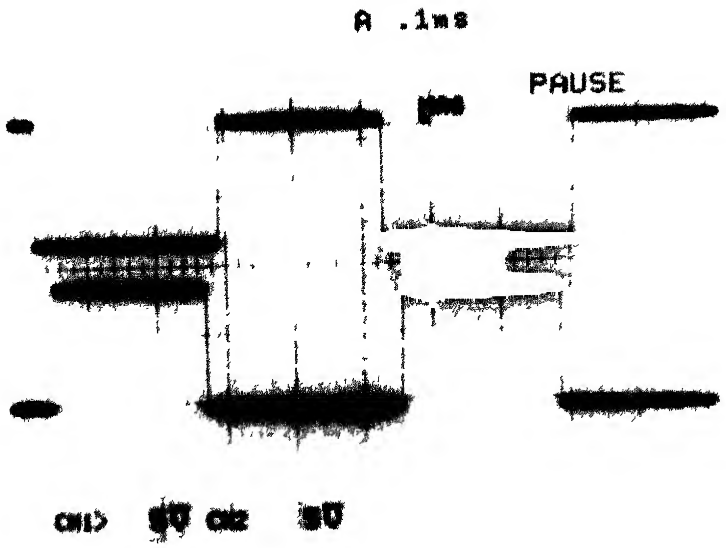


Figure 4 16· Output of blanking circuit (switching signal for IGBT's 1 and 2

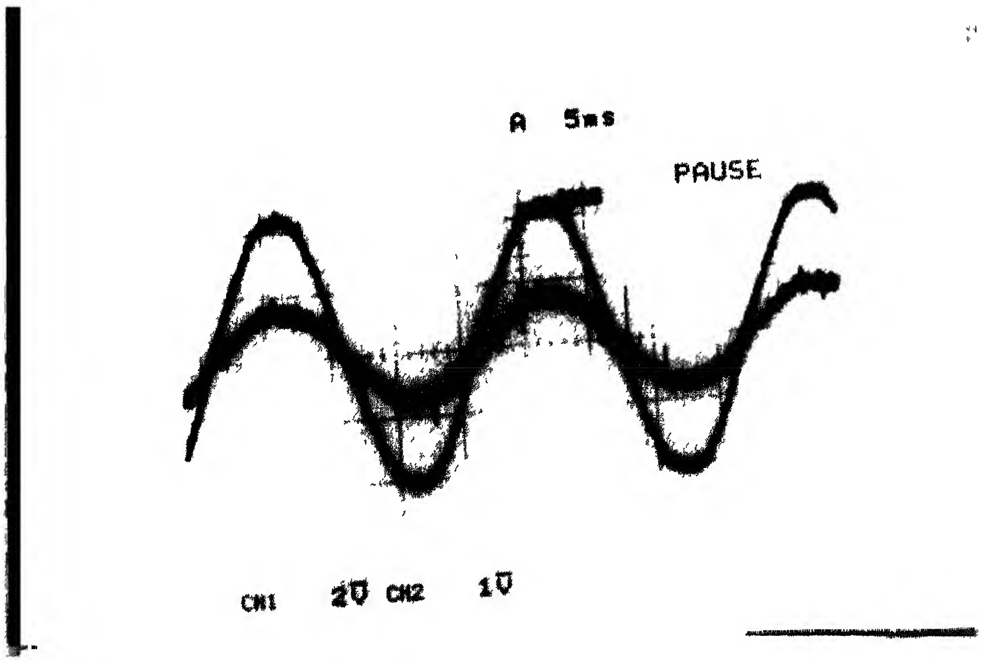


Figure 4 17: Supply voltage and Supply current waveform

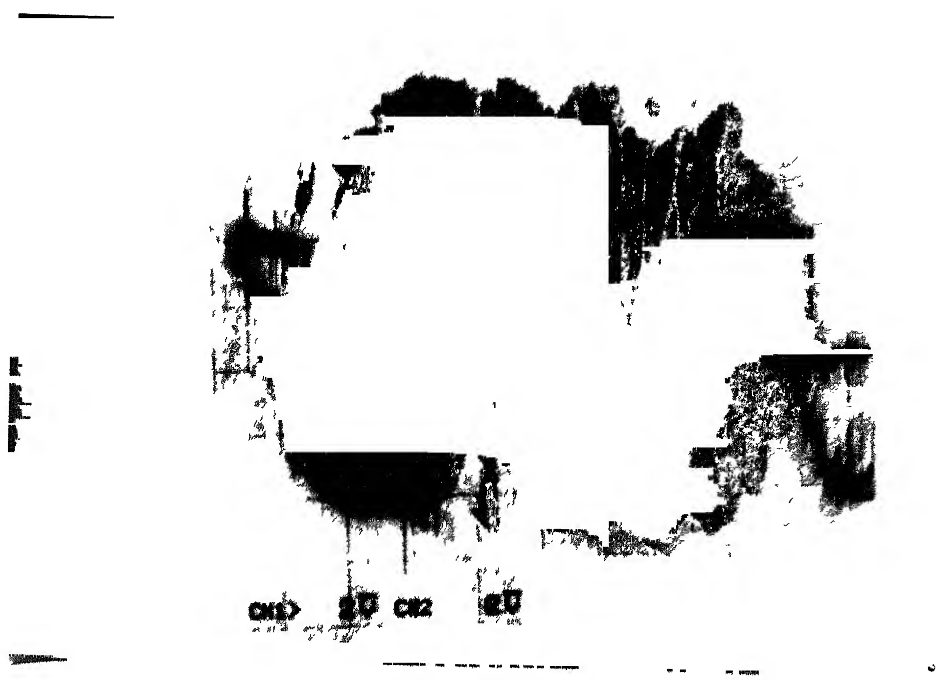


Figure 4 18 Supply voltage and Converter input voltage waveform

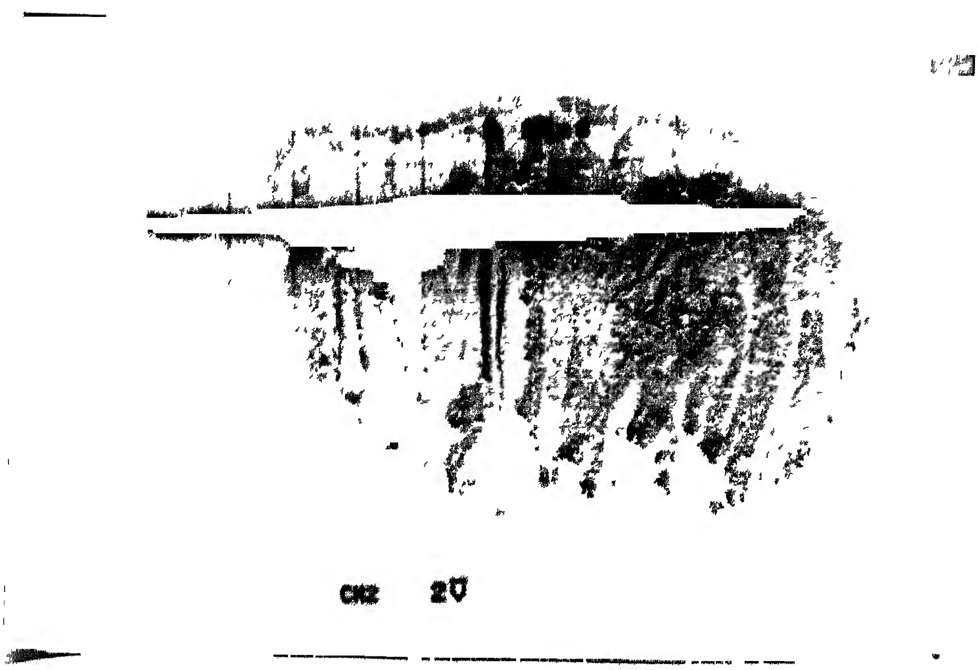


Figure 4 19 DC link voltage wave form

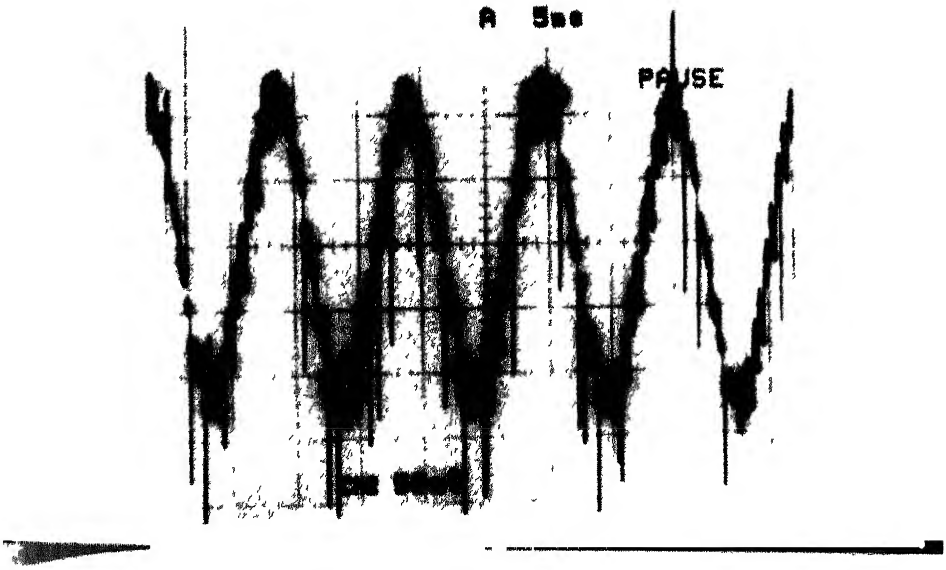


Figure 4.20 High frequency component in the DC Link voltage waveform

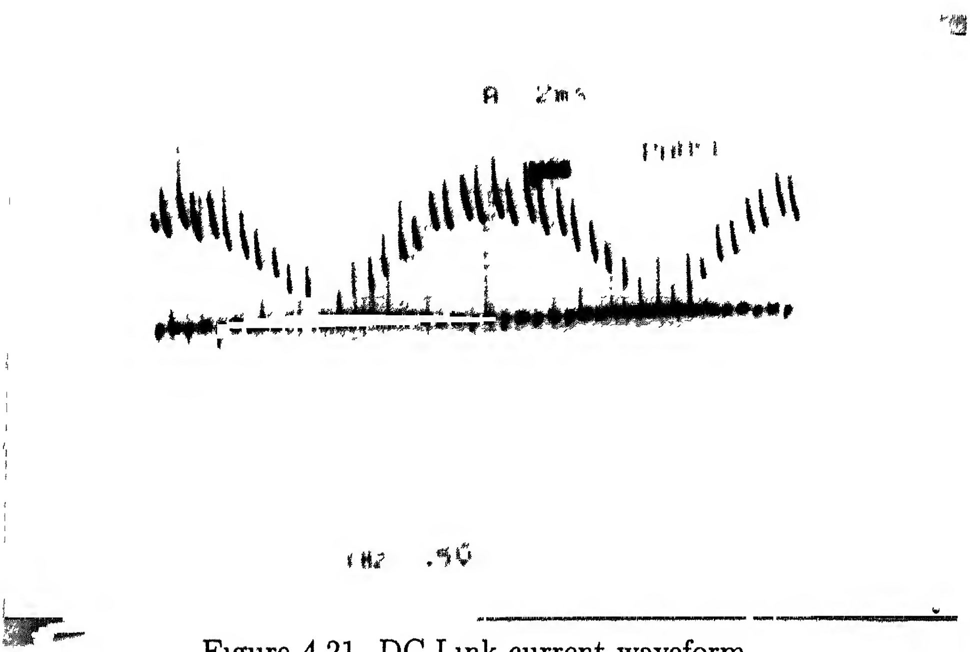


Figure 4 21 DC Link current waveform

Chapter 5

Application of the Synchronous Link Converter to Electric Traction

5.1 Introduction

In the field of electric traction, *dc* motors have been in use since long time However at present the three phase *ac* drive is becoming very common and significant for the modern electric traction drive systems. These drive systems are equipped with asynchronous traction motors featuring easy maintenance, high reliability and compact design. Such systems require converters on the motor coaches / locomotives, which rectify power from *ac* to *dc* and PWM inverters for converting the *dc* into three phase *ac* for feeding the asynchronous traction motors

In a modern regenerative single phase 25 kV traction drive one can use the Synchronous Link Converter as a front end converter, featuring an *ac* input current which is almost in phase with the supply voltage and controllable to almost sinusoidal waveform. In this chapter, the performance and analysis of Synchronous Link Converters as applied to the electric traction drive system is presented

Particular	Enforced Limits
Psophometric current	$\leq$ 10 0 A
D C component of current	$\leq$ 4 7 A
Second harmonic component of current	$\leq$ 8 7 A
Audio frequency component 1650 - 1750 hz 1950 - 2050 hz 2250 - 2350 hz 2550 - 2650 hz	 $\leq$ 400 mA amplitude $\leq$ 400 mA amplitude $\leq$ 400 mA amplitude $\leq$ 400 mA amplitude
High frequency component 5050 - 5100 hz	 $\leq$ 270 mA amplitude

Table 5 1 The Enforced Limits

5.2 Requirements of the Front end Converters for Electric Traction systems

1 The front end converters should ensure a power factor as near unity as possible

2 The converters should be designed in a way to keep the psophometric disturbance current, the *dc* component, the audio frequency components and the high frequency components within the enforced limits given in table 5 1

3 The converters should be designed in a way such as not to cause intolerable level of interference to the track circuits and the telecommunication equipments.

4 The front end converters should ensure four quadrant operation and the regenerative braking should be available from the maximum speed range upto near standstill.

5 The overhead catenary voltage fluctuates widely The converters should be provided with the necessary control to operate under such fluctuations With Indian railways, the power supply for over head catenary is 25 kV, 1 ϕ, 50 hz. The 25 kv being nominal voltage of the system, the variations in supply voltage is from 17.5 kV to 30 0 kV

6 The capacity of converter should be adequate to permit the continuous operation super dense crush loaded train (the maximum load which will come on the driving axle), under given operating conditions

7 The voltage ratings of switching devices used should be so chosen, that atleast 25 % margin is available after taking into consideration the *dc* link voltage and the voltage spikes on account of inductance and capacitance in the circuit

5.3 Psophometric Current :

It is a usual practice to install, the telecommunication lines in parallel along the track In the case of electric traction, the harmonic currents flowing in overhead catenary cause interference in the telecommunication lines The depth of interference is accessed by using a factor called psophometric disturbance current It is assessed by using an equivalent interfering current (J_p), where J_p is given by the following equation -

$$J_p = \sqrt{\sum_{n=1}^{59} (S_n\, I_n)^2} \tag{5 1}$$

where,

I_n is the n^{th} harmonic current in supply current

S_n is the noise assessment coefficient

The noise assessment co-efficient was established by the C C I T T (International Telegraph and Telephone Consultative Committee) in 1952 The noise assessment co-efficient or the weightage factor for different frequencies are given in Appendix I The variation of weightage factor with the harmonic number is given in fig 5 1

Fig 5 1 suggests that the weightage factor is very small for lower order harmonics and therefore psophometric current depends mainly on the higher order harmonics Also the weightage factor has a peak around 1000 hz These factors are to be considered in the design of Synchronous Link Converters for electric traction applications

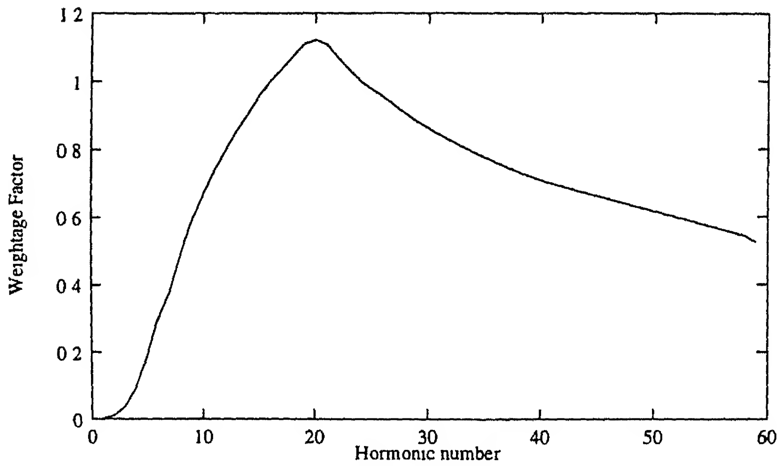


Figure 5 1 Variation of the weightage factor with harmonic number

5.4 Principle of Operation :

In the case of electric traction, power involved is very high Also for the purpose of redundancy, several stages of Synchronous Link converters are being used These converters are supplied from the single phase over head *ac* catenary through the pantograph and a step down transformer The transformer has a single primary winding and multiple secondary windings Each of these secondary windings, feed a single phase Synchronous Link Converter The transformer windings are so designed that the percentage reactance of all secondary windings are maintained unchanged, irrespective of the combined or isolated operation of the windings

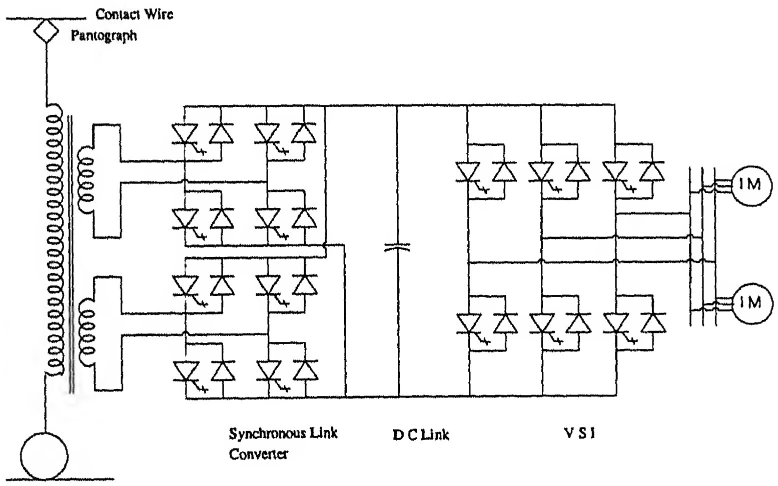


Figure 5 2 Basic two stage Synchronous Link Converter

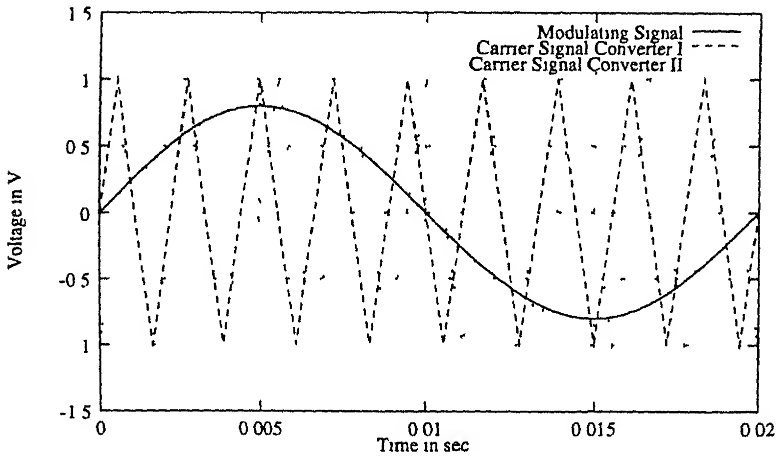


Figure 5 3 Carrier signals of a Two stage Synchronous Link Converter

Fig 5 2 gives a case, where two Synchronous Link converters are operated in parallel The pantograph collects the power from overhead catenary The pantograph is connected to primary side of a step down traction transformer The transformer has two secondary windings each feeding a Synchronous Link Converter These converters feed a common *dc* link circuit The *dc* link feeds PWM inverter, which converts the *dc* into the three phase *ac* for feeding the asynchronous traction motors

Each of the two Synchronous Link Converters are operated as an independent unit These two converters are operated with a common modulating signal The carrier signals of the individual converters are equally displaced within one half of the carrier period by an angle $\pi/2$ radians Fig 5 3 gives the carrier signals for the converters *I* and *II* The voltage waveform at the input terminals of the individual converters are given in figs 5 4 and 5 5 respectively

These two Synchronous Link converters are effectively connected in series, on the primary side of traction transformer by virtue of the common step down transformer The equivalent voltage as seen from the primary side of transformer is sum of the input voltage of two converters Fig 5 6 gives the input voltage waveform of two converters, on the primary side of transformer The equivalent circuit is given in the fig 5.7 , where V_{i1p} is the fundamental component of equivalent input voltage of the two converters on the primary side of transformer This equivalent circuit resembles one discussed in of chapter 3 , however the synchronous link inductor has been realized by utilizing the leakage inductance of transformer This results in reduction in the cost, volume, weight, losses etc associated with an independent

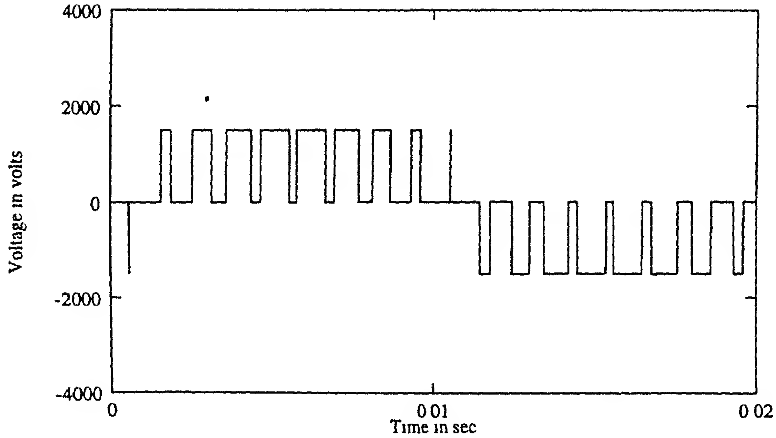


Figure 5 4 Converter input voltage waveform at transformer secondary I

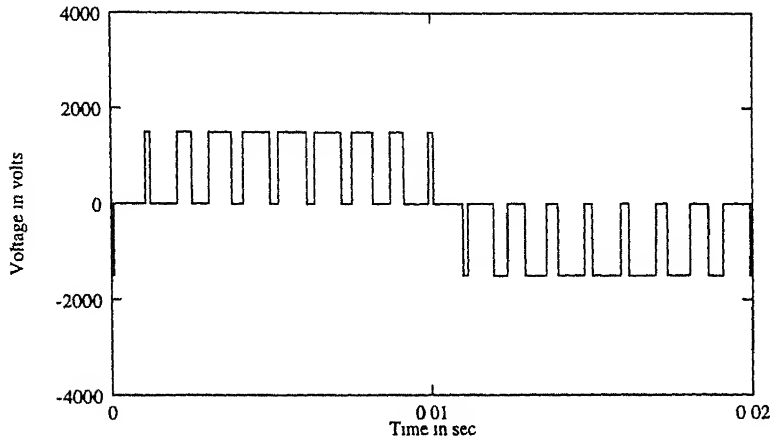


Figure 5 5 Converter input voltage waveform at transformer secondary II

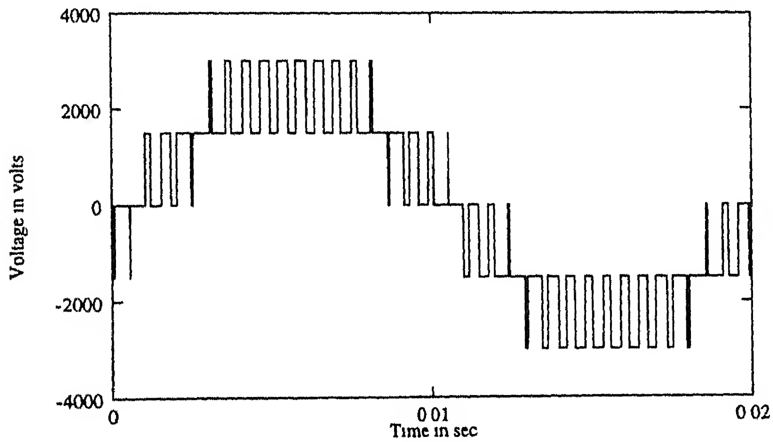


Figure 5 6 Converters input voltage waveform at transformer primary

synchronous link inductor

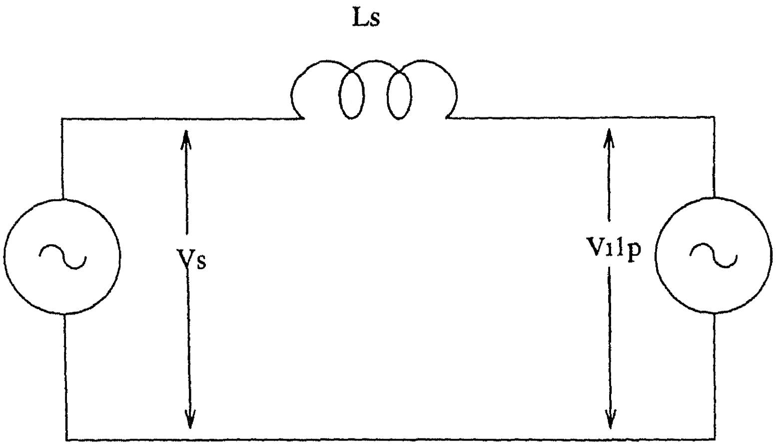


Figure 5 7 Equivalent Circuit referred to transformer primary

If triangular carrier frequency of each of the two converters are say f_c, then the equivalent carrier frequency on the primary side of transformer will be $4f_c$ This eliminates the low order harmonics in the converter input voltage waveform on the primary side of traction transformer, and in the supply current

In general if 'n' single phase Synchronous Link Converters are operated in parallel, then switching instants of the individual converters are obtained, by using a common modulating signal and the triangular carrier waves of respective converters are phase shifted by (one half the carrier frequency period / n) i e π/n radians with respect to each other

If the microprocessors are used for generation of switching signals, then the switching instants for each of converters can be obtained by trigonometric relations as given by following equations -

$$\alpha_{2i-1} = \frac{\pi}{2R}\left[4i - 3\ 0 - M_f sin\left((2i-2)\frac{\pi}{R} - \delta + \beta\right)\right] + \beta \qquad (5\ 2)$$

$$\alpha_{2i} = \frac{\pi}{2R}\left[4i - 1\ 0 + M_f sin\left((2i-1)\frac{\pi}{R} - \delta + \beta\right)\right] + \beta \qquad (5\ 3)$$

where,

i = switching instant.

α = switching angle

$R = \frac{f_c}{f_s}$

M_f = the modulation index
δ = phase angle difference between the modulating signal and the supply voltage
β = phase difference between the carrier waves of the converters operating in parallel
$= m \times \frac{one\ half\ of\ the\ carrier\ period}{n}$ for $n \geq 2$

where,
$m = 1$ for second converter
$m = 2$ for third converter
$m = (n-1)$ for n^{th} converter

5.5 Digital Simulations :

5.5.1 Determination of the power rating of the converter

For obtaining the power rating of converter the following data are used

1 Weight of the dense crush loaded train (or weight with the maximum load) = 800 tonnes

2 Number of motor coaches in a rake = 4

3 Number of trailer coaches in a rake = 8

4 Average acceleration upto speed of 40 kmph = 0 42 m/sec^2

5 Gear Ratio used = 4 87

6 Number of motors used = 4

7 Efficiency of motors used = 0 94

8 Efficiency of inverter used = 0.98

Starting tractive effort $= \frac{0\ 42 \times 1\ 1 \times 800\ 0 \times 10^3}{9\ 81} = 37676\ 0\ \ kG$
Starting tractive effort / motor $= \frac{37676\ 0}{4\ 0 \times 4\ 0} = 2355\ 0\ \ kG$
Starting torque developed by the motor $= \frac{2355\ 0 \times 0\ 915 \times 9\ 81}{2\ 0 \times 4\ 87} = 2170\ 0\ \ nm$
Motor speed corresponding to 40 kmph $= \frac{40\ 0 \times 1000\ 0 \times 4\ 87}{\pi \times 0\ 915 \times 60\ 0} = 1130\ \ rpm$

Power output at 40 kmph $= \frac{2170\ 0 \times 2\ 0 \times \pi \times 1130\ 0}{60\ 0} = 257\ 0\ \ kW$

Power rating of the converter / motor coach $= \frac{4\ 0 \times 257\ 0}{0\ 94 \times 0\ 98} = 1120\ 0\ \ kW$

The rating of the converter determined is only approximate, mainly for use in the digital simulations In actual practice the converter rating is decided by taking into consideration the entire system The adhesion co efficient, power requirement for the operation of motor coaches on the given gradient are to be considered, for determining the actual power rating of converter

5.5.2 The Psophometric Current Characteristics of a Single Stage and a Two Stage Synchronous Link Converters

For the purpose of analyzing psophometric characteristics of a Single stage and a Two stage converters, the following data are used

1 Traction power output = 1120 0 kW

2 Transformer Primary Voltage = 22500 0 V

3 Transformer Secondary Voltage = 680 0 V

4 DC link Voltage = 1500 0 V

The simulations were made using a dedicated program The inverter load was modeled by a constant current source corresponding to traction power output of 1120 0 kW The asymmetric regular sampled PWM scheme was used for the converters The switching instants for the individual converters were obtained from equations 5 2 and 5 3 For getting the conservative results, the supply inductance were neglected The converters were operated as an individual unit with a common *dc* link The *dc* link capacitor was designed to keep the dynamic variations in *dc* link voltage within 5 0 % The switching devices were considered ideal The power losses in the supply, traction transformer and out put filter capacitors were neglected

The simulation were made to study the following characteristics

1 Effect of changing the Synchronous link inductance

2 Effect of changing the Switching frequency

1. Effect of changing the Synchronous Link Inductance :

The simulations were done with a carrier frequency of 450 hz The synchronous link inductor has been varied from a minimum value ($L_{min} = 0\ 1mH$ has been used for the simulation) to a maximum value as given by the equation 3 39 The input currents on the primary side of traction transformer are used to for determining the psophometric disturbance current The results of simulations for a single stage and a two stage converters are given in fig 5 8

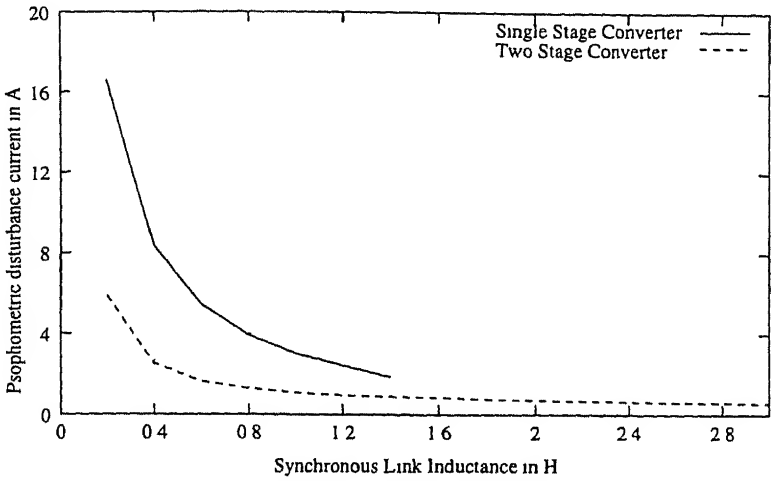


Figure 5 8 Psophometric current characteristic of a single stage and a two stage converters for variations in the synchronous link inductance

2. Effect of changing the Switching frequency .

The simulations were done at one particular value of synchronous link inductor (a typical value of 0 7 mH has been used for simulation) The carrier frequency was varied from a minimum value of 400 hz to a maximum value of 1000 hz The inputs currents on the primary side of transformer are used for determining the psophometric currents The results of simulation for a single stage and a two stage converters are shown in the fig 5 9

From these simulation studies the following details can be obtained

1 Figs 5 8 and 5 9 suggests that a two stage converter gives better performance than a single stage converter from psophometric disturbance current characteristic consideration The reduction in psophometric current can be related to the converter input voltage harmonic characteristics Fig 5 10 gives the simulated results of the variation of converter input voltage harmonics with the

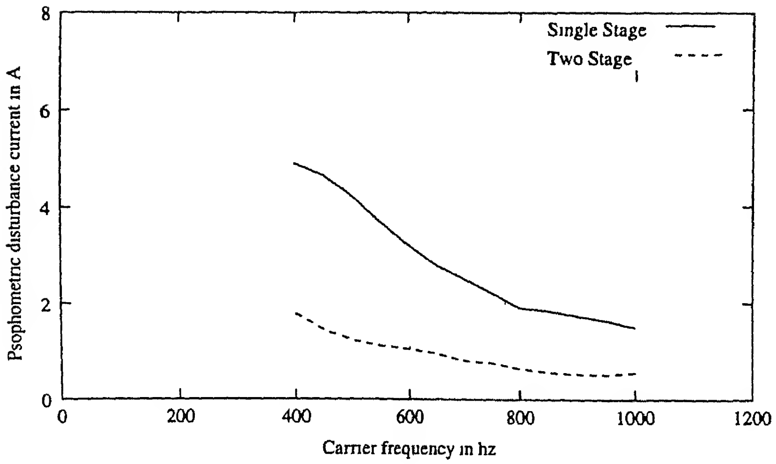


Figure 5 9 Psophometric current characteristic of a single stage and a two stage converters for variations in the switching frequency

modulation index for a two stage converter Fig 5 10 indicates that in the case of Two stage converter, the dominant harmonic appear at frequency around $4f_c$ (where f_c is the frequency of carrier wave), unlike a single stage converter where the dominate harmonics appear at frequency around $2f_c$ Since the harmonic currents are directly proportional to the harmonic voltages and inversely proportional to the harmonic frequency the magnitude of harmonic currents and hence the psophometric disturbance current gets reduced

2 With the increase in carrier frequency, the psophometric current reduces Also in the case of Single stage converter, to get the same psophometric current characteristics as in the case of the Two stage converter, the carrier frequency have to be doubled

3 In the case of Two stage converter, though the psophometric current reduces with the increase in carrier frequency, but however the reduction is not much Hence a carrier frequency of about 450 hz may be considered as optimum for a Two stage converter, from psophometric current characteristics consideration This will ensure the reliable operation of GTO thyristors and results in the lower switching losses.

4 With the increase in value of synchronous link inductance, there is a better filtering ability at the converter input terminal Hence the input harmonic currents and the psophometric currents reduces

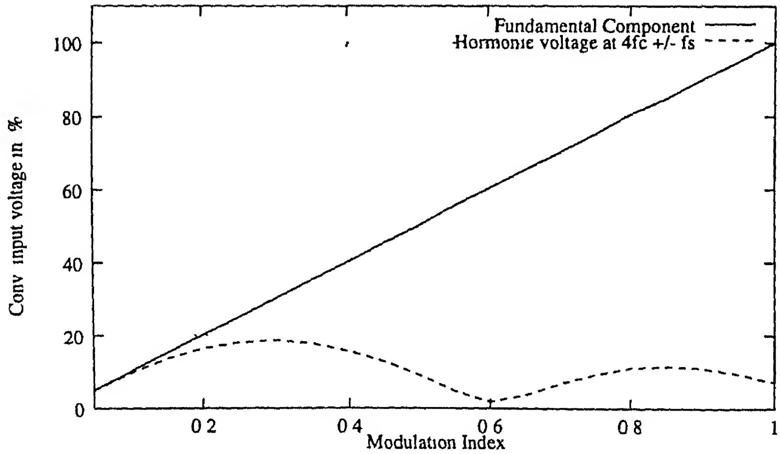


Figure 5 10 Calculated input harmonic voltage of a two stage synchronous link converter

5 In the case of Two stage converter, the psophometric current reaches a minimum value at a certain value of synchronous link inductance, which is well within the maximum limit of inductance for given power rating of the converter This factor favours the utilization of leakage inductance of the transformer, for designing the Synchronous Link Converter This in an additional advantage as there will be a saving in volume and weight which is a major factor to considered in the case of modern electric traction drive However such scheme results in the higher value of harmonic currents in the secondary windings of traction transformer This factor have to be considered in the design of traction transformer These harmonics get cancelled on the primary winding of traction transformer

5.5.3 Effect of Changing the Converter Power Output :

In the case of electric traction, it is essential that the converters operate at different power levels, with the minimal harmonic injection into over head catenary supply The simulations are made to study the psophometric current characteristics under varying power outputs from the converter For the purpose of simulation the data given in section 5 5 2 are used The input current on the primary side of transformer are used to determine the psophometric current The results of the simulations for a Single stage and a Two Stage converters are shown in the fig 5 11

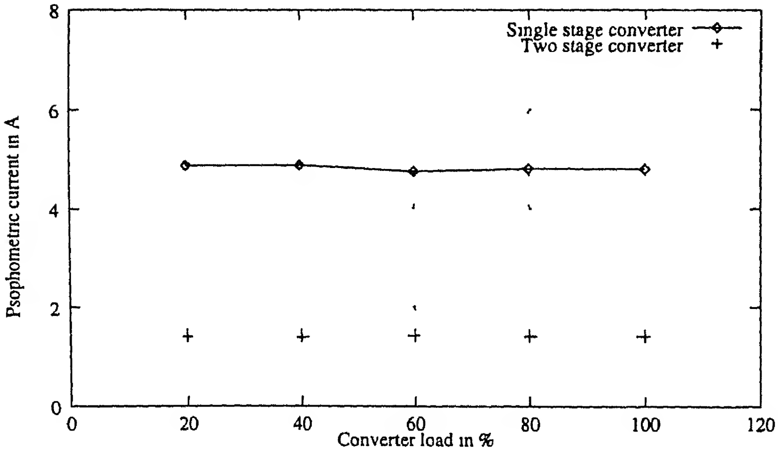


Figure 5 11 Psophometric current characteristic of a single stage and a two stage converters for variations in the power output

Fig 5 11 indicates that the psophometric current remains constant with the change in power output from the converter In the case of electric traction, the synchronous link inductance is realized by utilizing the leakage reactance of transformer Hence the value of synchronous link inductance is low With a low value of synchronous link inductance, the effect of varying converter power output results in the variation of modulation index over a narrow range The magnitude of harmonic voltage at converter input may be assumed to be a constant, when the modulation index is varied over a narrow range Hence the harmonic currents at input and hence the psophometric current at the over head catenary remains constant

5.5.4 Performance Characteristics of a Single Stage, a Two Stage, a Three Stage and a Four Stage converters :

Due to use of the single phase supply (even at high power), a large voltage drop and hence higher transmission losses are expected in the over head catenary supply Hence it becomes necessary to maintain pf near unity, as a low power factor will result in higher voltage drop and higher transmission losses in the over head catenary supply Also the lower power factor may results in the over loading of equipments in the traction substation

Harmonics in the overhead catenary supply, has number of undesirable effects such as the excitation of system resonance, decrease in the efficiency owing to the

increased losses due to the harmonics current, saturation and non linear behaviour of the traction transformer, maloperation of the signals and the interference with telecommunication lines which usually run by the side of track

With these considerations, the single stage, the two stage, the three stage and the four stage converters were analyzed The following data are used in the simulations

1 Traction Power output per motoı coach = 1120 0 kW

2 Transformer primary voltage = 22500 0 V

3 Transformer secondary voltage = 680 0 V

4 DC link voltage = 1500 0 V

5 Synchronous link inductance = 0 7 mH

6 Carrier frequency = 450 0 hz

7 Number of motor coaches per rake = 4 0

The simulations were made using a dedicated program The inverter load was modeled as a constant current source, corresponding to the traction power output of 1120 0 kW (power out put corresponding to a single motor coach has been considered for simulation Four such similar units are operated in parallel), the out put filter capacitoı was designed to keep the dynamic variations in *dc* link voltage within 5 % of the rate value, and the switching devices were considered to be ideal

The simulated primary current waveforms, the converter input voltage waveforms referred to the primary side of the transformer and the harmonic spectrum for a single stage, two stage three stage and a four stage converters are given in figs 5 13 to 5 27 (considering a single motor coach only) A comparison table is given in table 2 (considering all four motor coaches operating in parallel)

Table 5 2 suggests that for the power rating under consideration, the four stage converter gives optimum performance, since the psophometric current, the *dc* component, the second harmonic component, the audio frequency components and the high frequency components are all within the enforced limits

Table 5 3 gives the comparison of various parameters used in the digital simulation (values used per motor coach) It suggests that with the increase in the number

Particular	Enforced Lim	Single stage conv	2 stage conv	3 stage conv	4 stage co
Psophometric current	≤ 10 0 A	18 40	5 64	3 94	2 49
D C component	≤ 4 7 A	0 85	0 32	0 24	0 04
Second harmonic component	≤ 8 7 A	0 04	0 04	0 04	0 04
Audio frequency component					
1650 hz	≤ 400 mA ampl	3716 0	7100 0	165 2	308 0
1750 hz	≤ 400 mA ampl	1680 0	1604 0	132 8	201 68
1950 hz	≤ 400 mA ampl	2264 0	5144 0	206 0	73 5
2050 hz	≤ 400 mA ampl	1584 0	1296 0	70 0	192 6
2250 hz	≤ 400 mA ampl	14 0	28 0	208 4	86 5
2350 hz	≤ 400 mA ampl	536 0	56 4	915 2	139 2
2550 hz	≤ 400 mA ampl	136 0	13 4	1280 0	60 52
2650 hz	≤ 400 mA ampl	268 0	62 4	1536 0	201 4
High frequency component					
5050 hz	≤ 270 mA ampli	476 0	152 0	318 4	0 0
5100 hz	≤ 270 mA ampli	0 0	0 0	0 0	0 0
Distortion factor		0 9964	0 9994	0 9994	0 9998
Displacement factor		0 9993	0 9992	0 9995	0 9966
power factor		0 9958	0 9985	0 9989	0 9965

Table 5 2 Disturbance characteristics of a Single stage , a Two stage, a Three stage and a Four stage converters

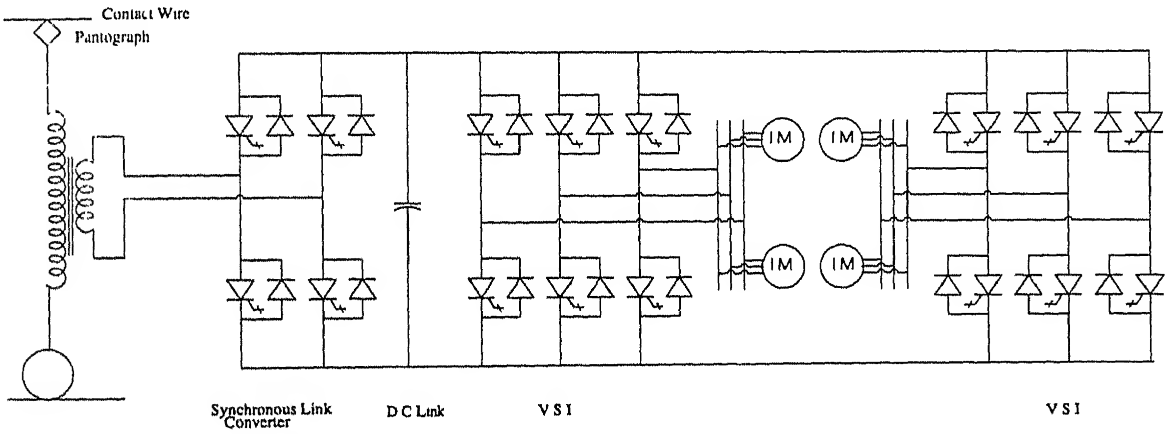


Figure 5 12 Single Stage converter

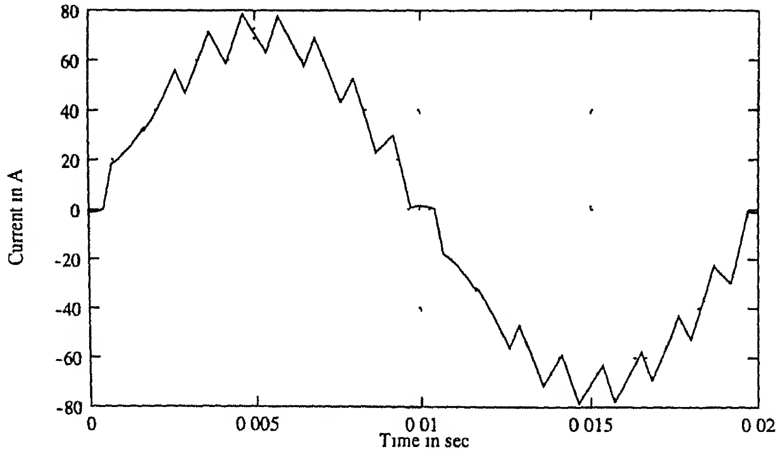


Figure 5 13 Input current waveform of a Single Stage converter

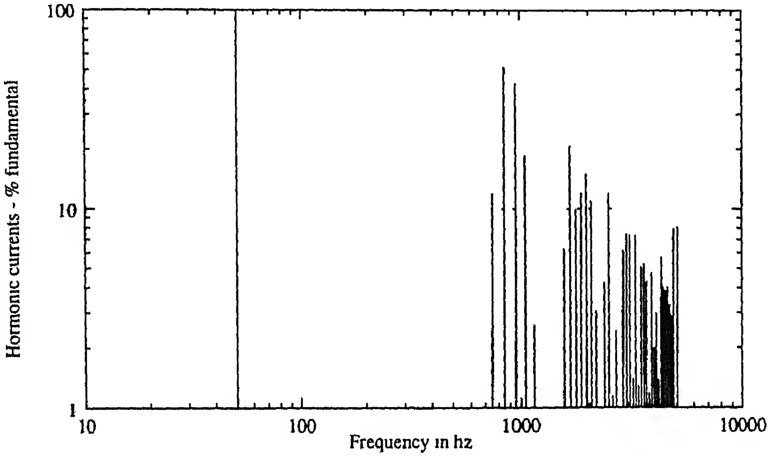


Figure 5 14 Harmonic Spectrum of input current of a Single Stage converter

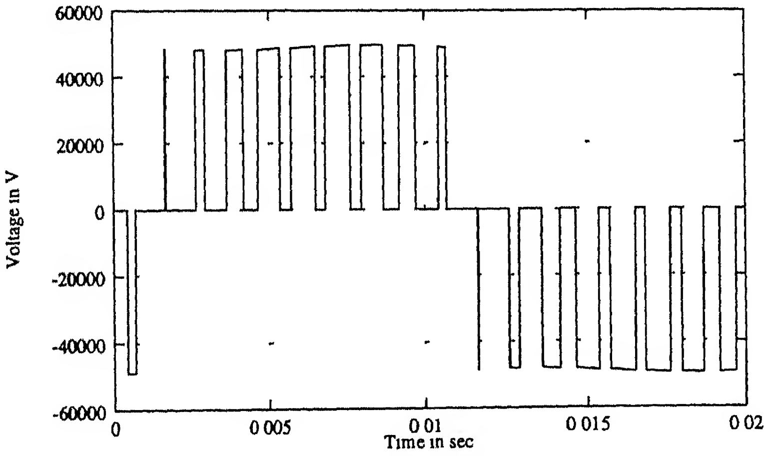


Figure 5 15 Input Voltage waveform of a Single Stage converter referred to primary

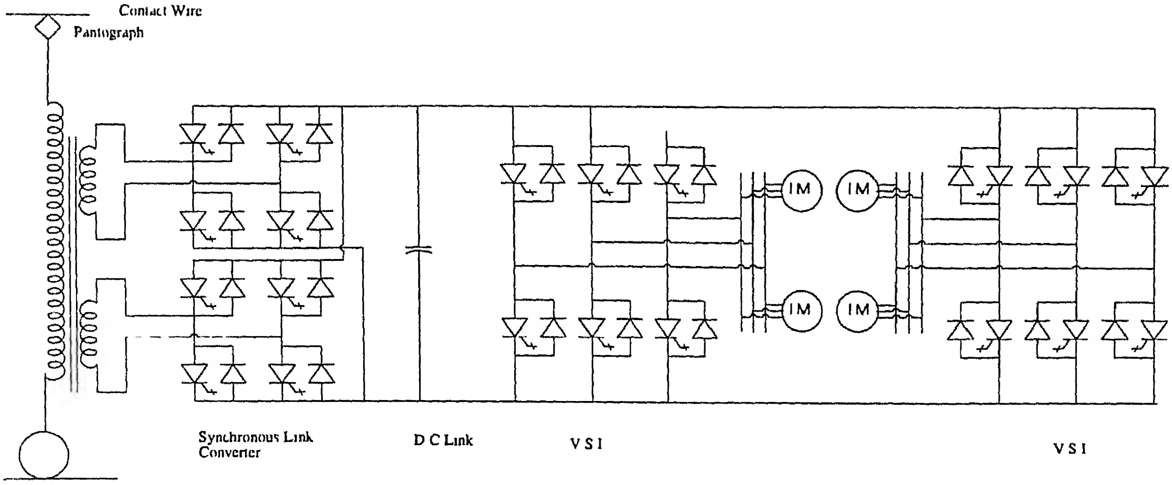


Figure 5 16 Two Stage converter

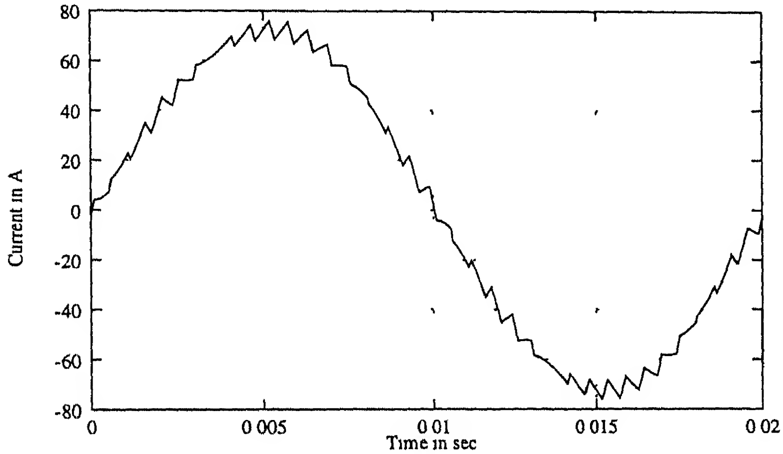


Figure 5 17 Input current waveform of a Two Stage converter

Particular	Single stage conv	Two stage conv	Three stage conv	Four stage conv
Total Power rating	1120 0 kW	1120 0 kW	1120 0 kW	1120 0 kW
Power Rating / stage	1120 0 kW	560 0 kW	374 0 kW	280 0 kW
Primary Voltage	22500 0 V	22500 0 V	22500 0 V	22500 0 V
Secondary Voltage	680 0 V	680 0 V	680 0 V	680 0 V
DC link voltage	1500 0 V	1500 0 V	1500 0 V	1500 0 V
Pry rms current at upf	50 0	50 0	50 0	50 0
Sec current / stage at upf	1647 0	824 0	549 0	412 0
Value of L_s	0 7 mH	0 7 mH	0 7 mH	0 7 mH
Transformer Sec KVA rating	1120 0	560 0	374 0	280 0
L_s based on Sec rating	53 3%	26 6%	17 8%	13 3%

Table 5 3 The Parameters used in digital simulation

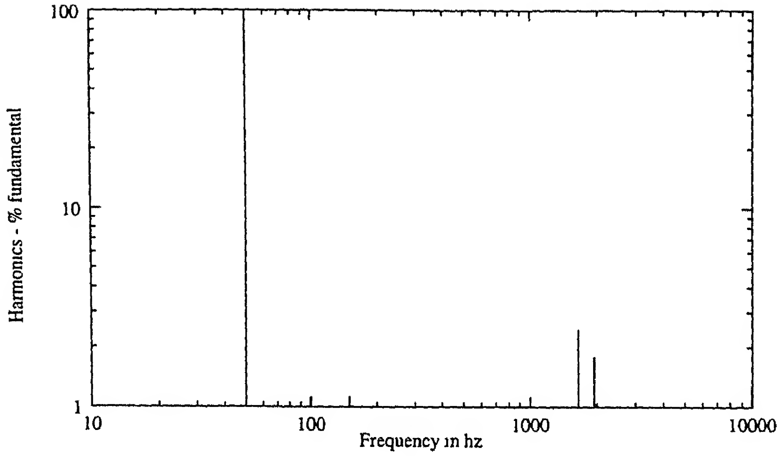


Figure 5 18 Harmonic Spectrum of input current of a Two Stage converter

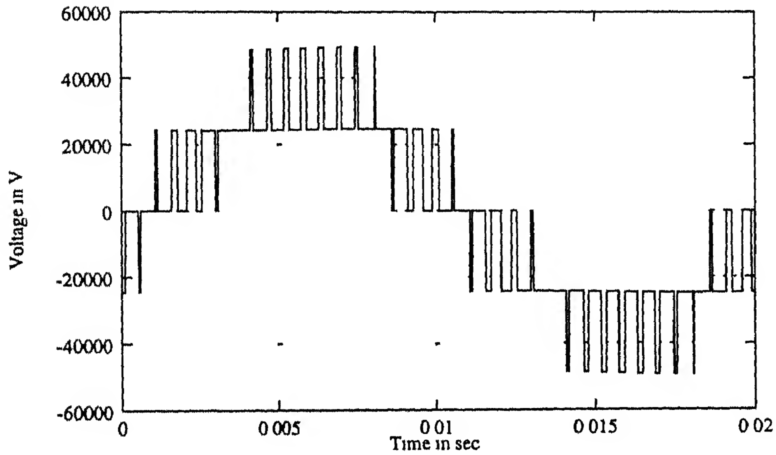


Figure 5 19. Input Voltage waveform of a Two Stage converter referred to primary

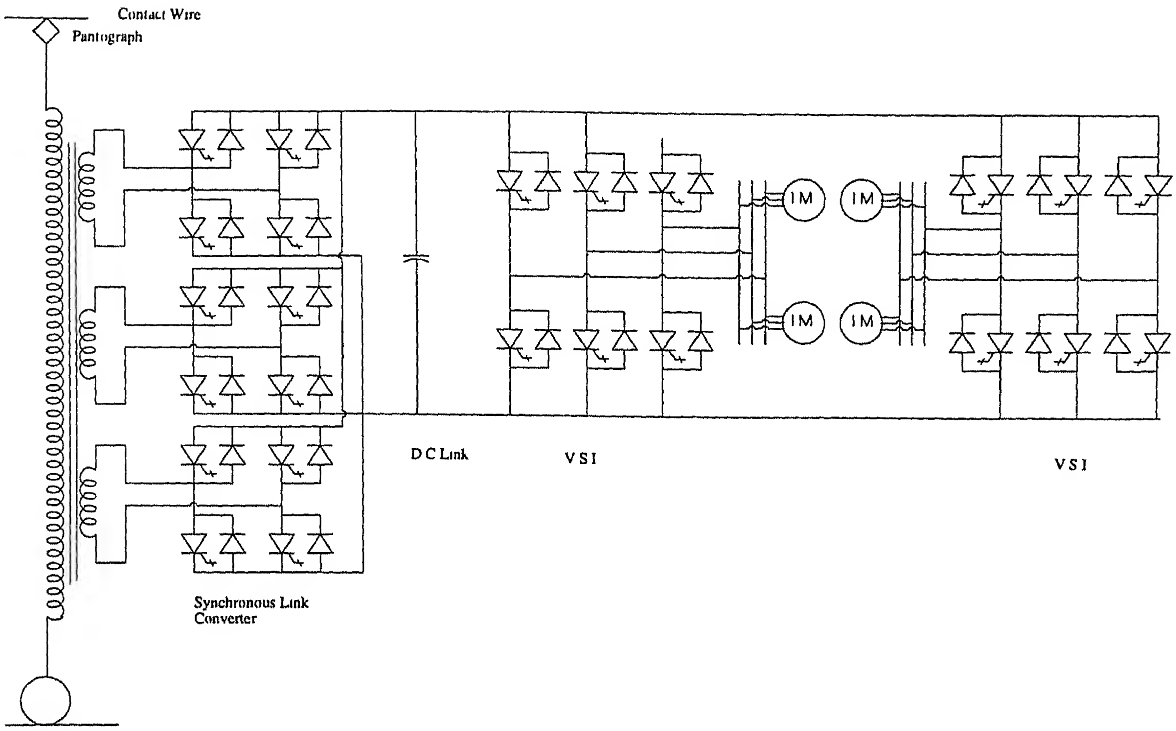


Figure 5 20 Three Stage converter

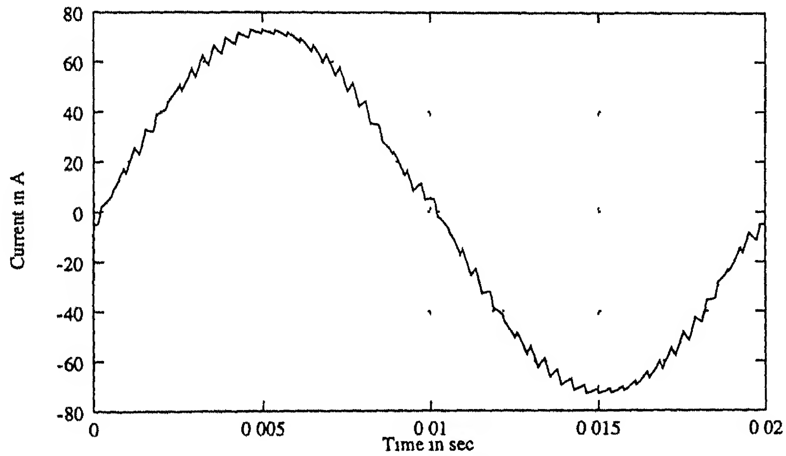


Figure 5.21 Input current waveform of a Three Stage converter

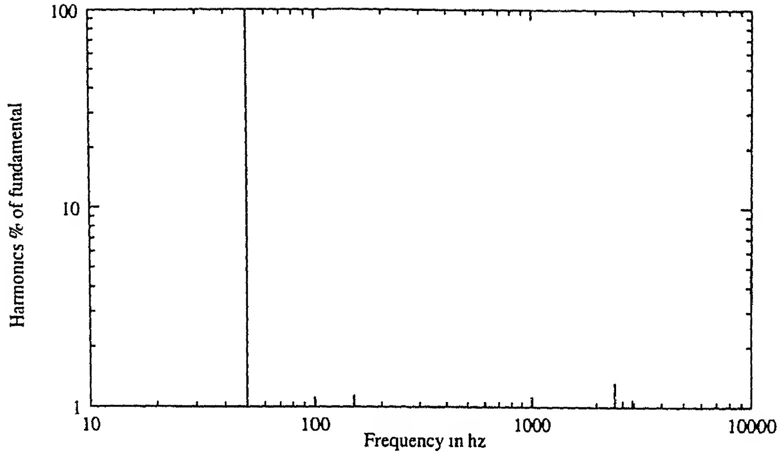


Figure 5 22 Harmonic Spectrum of input current of a Three Stage converter

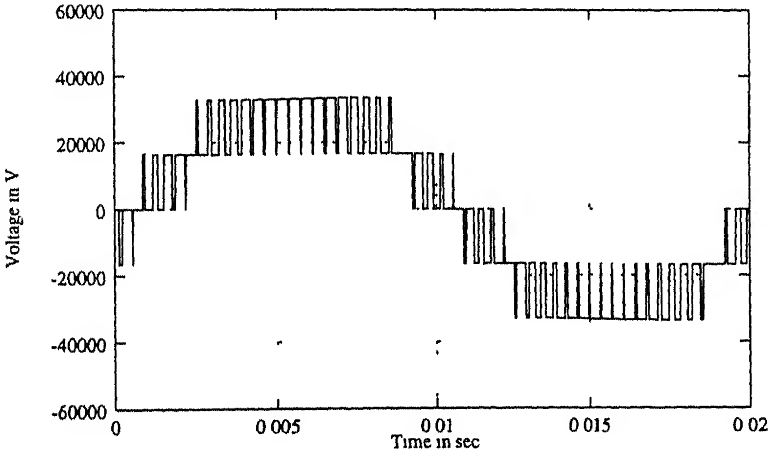


Figure 5 23 Input Voltage waveform of a Three Stage converter referred to primary

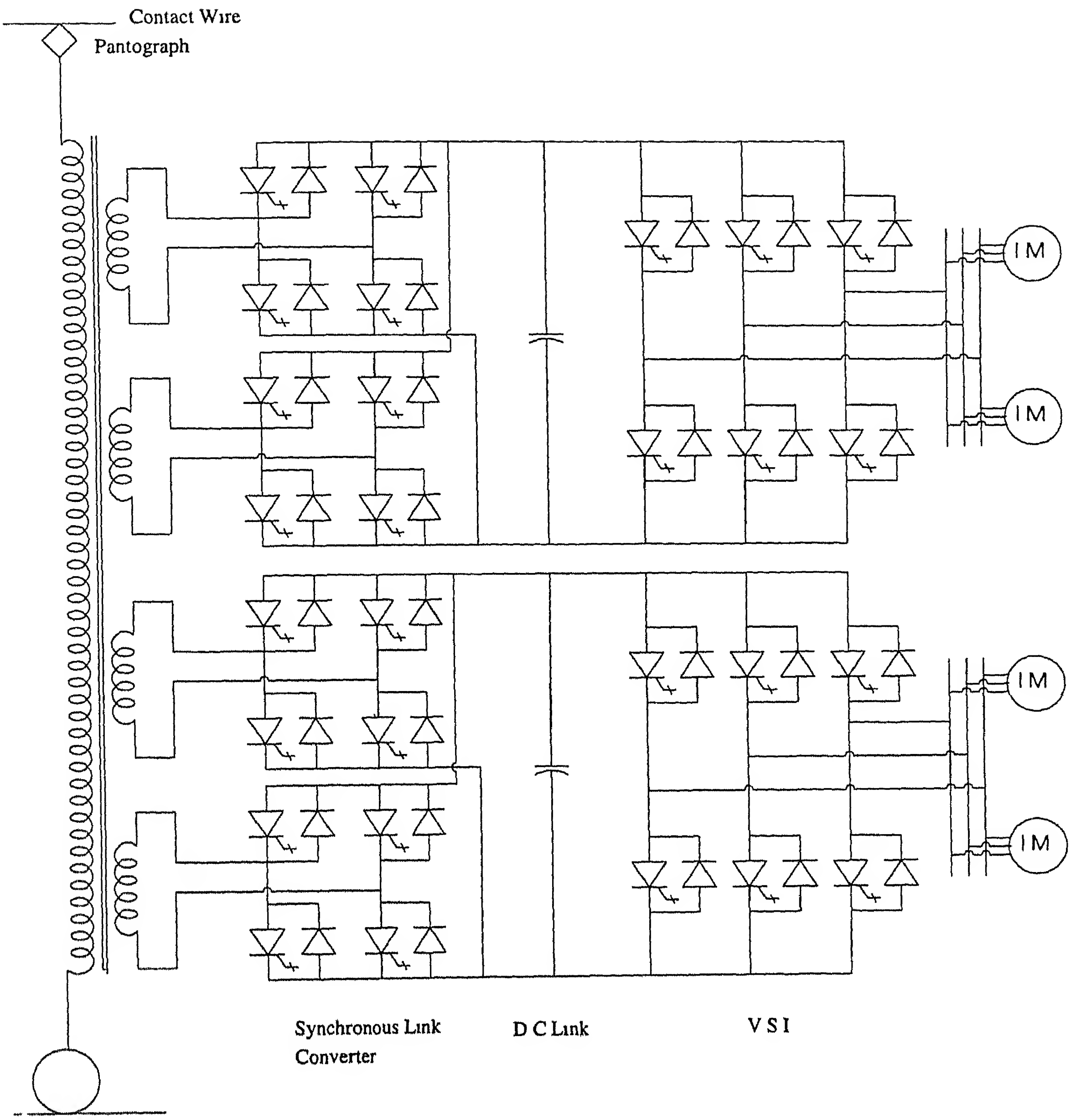


Figure 5 24 Four Stage converter

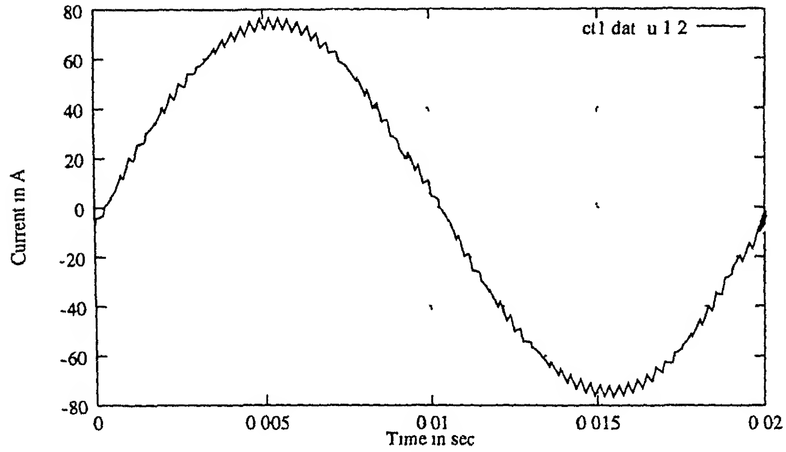


Figure 5 25 Input current waveform of a Four Stage converter

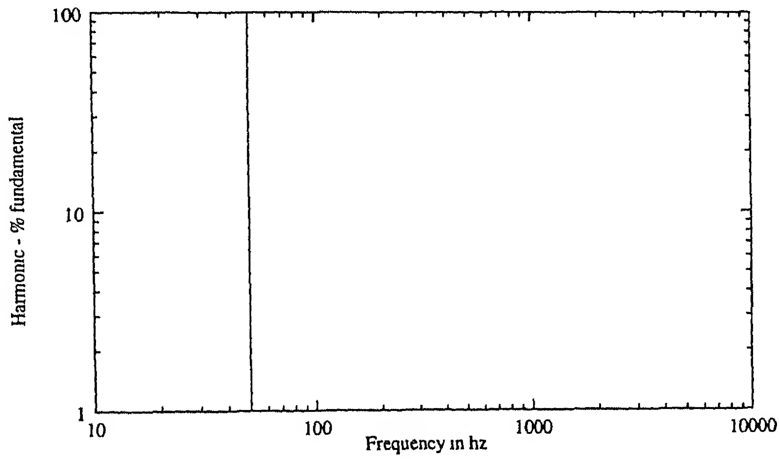


Figure 5 26 Harmonic Spectrum of input current of a Four Stage converter

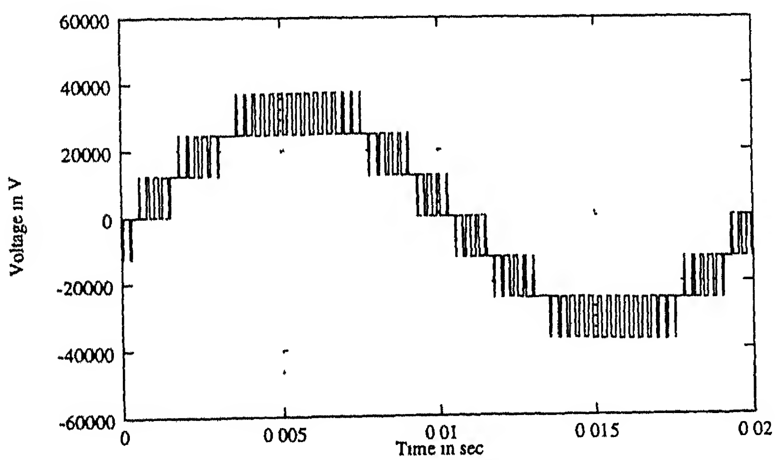


Figure 5 27 Input Voltage waveform of a Four Stage converter referred to primary

of stages, the synchronous link inductance based on the transformer secondary kVA rating reduces Therefore it can be easily realized by utilizing the leakage reactance of traction transformer windings This can be considered as one of the major advantage as it results in the reduction in volume, weight, losses etc which are major concern in the modern electric traction drive systems

With the increase in number of stages, we find that the device current rating reduces This may result in the better performance of GTO thyristors, due to reduced switching losses at a constant carrier frequency Alternatively one can increase the carrier frequency to keep the switching losses same as that obtained with a Single stage converter This increase in the carrier frequency results in overall better performance of the multistage converter

Also with the increase in number of stages, the device rating may reduce to a level, within the power capability of IGBT's, currently available Since the switching frequency of IGBT's are higher than GTO thyristors, a better performance can be obtained from a Synchronous Link Converters constructed with the IGBT's The use of IGBT's in the construction of Synchronous Link Converter results in reduction in the value of synchronous link inductance, for obtaining, the characteristics same as one obtained with Synchronous Link Converter constructed by utilizing GTO thyristor as switching devices

5.6 Effects of the Catenary Voltage Variations :

In the case of electric traction, the over head catenary voltage fluctuates widely The variation of supply voltage is in range from 17 5 kV to 30 0 kV The front end converters should be designed to operate with wide variations in the catenary supply voltage

The Synchronous Link Converter can be designed to operate with such large variations in the supply voltage by means of the *'Limit Tracing Vector Control'*

With the decrease in catenary voltage from the designed value of 22500 0 V, the input currents to Synchronous Link Converter increases at unity power factor When the input current reaches an upper limit called the 'Cut Off Current Limit', the input current has to be limited The Limit Tracing Vector control automatically limits the input current at 'Cut Off Current Limit' The Cut Off current Limit depends upon rms current rating of the switching devices used This results in a

reduction in the power input to the converter and hence the power out put from the converter The power factor is maintained at unity Thus a Synchronous link Converter can be operated continuously at the reduced catenary voltage, at unity power factor with slight reduction in the power capability of the converter

With increase in the catenary voltage from the designed value, the magnitude of converter input voltage V_{i1} and the modulation index has to be increased, so as to keep the power balance across converter But with an increase in modulation index, the turn off time of switching devices reduces The Limit tracing Vector control will allow the converter input voltage and the modulation index until an upper limit called "off Time Limit" is reached Beyond this limit, the magnitude of converter input voltage is maintained constant, and the power factor is adjusted for maintaining the power balance across converter Thus a Synchronous Link Converter is operated intentionally at a reduced power factor

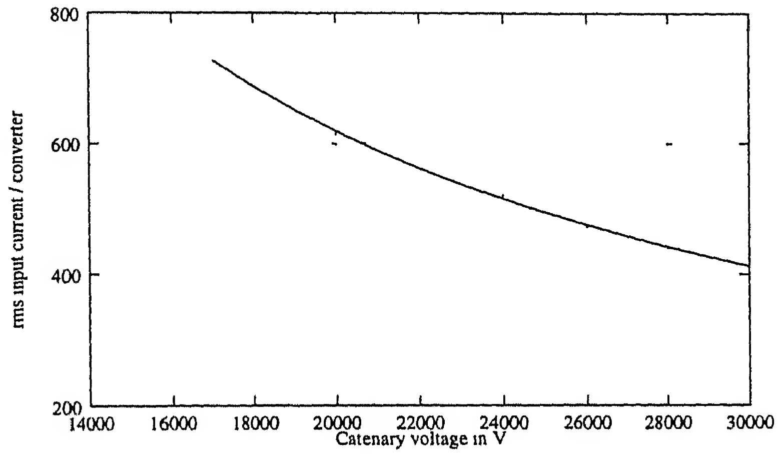


Figure 5 28 Variations of the input current of a Three Stage converter with the change in the catenary voltage

Fig 5 28 shows the variation of converter input current of a stage of a Three stage Synchronous Link Converter with the change in catanary voltage Fig 5 28 suggests, that if the rms current rating of switching devices are chosen to operate at lower limit of the catenary voltage, then a Three stage converter can operate without incorporating the 'Cut Off Limit Control'.

Fig 5 29 shows the variation of modulation index of a stage of a Three stage Synchronous Link Converter, with change in the catenary voltage Fig 5 29 suggests that for a chosen value of synchronous link inductance and the dc link voltage, the

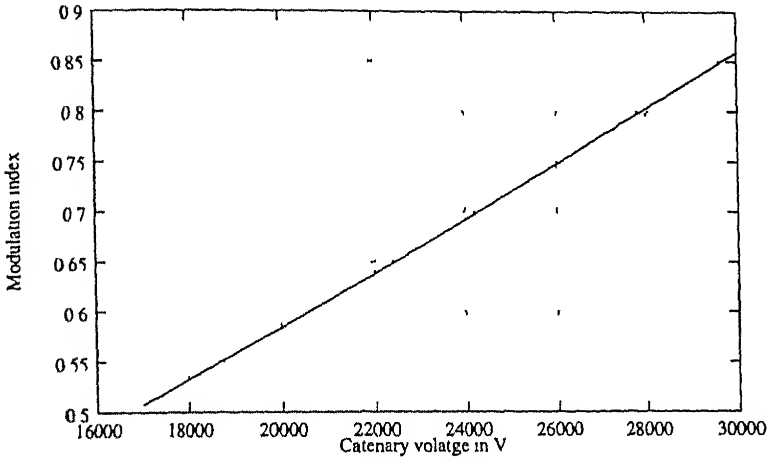


Figure 5.29 Variations of the modulation index of a Three Stage converter with the change in catenary voltage

Three stage converter can operate without incorporating the off time limit control. Hence through the proper choice of *dc* link voltage, synchronous link inductance and rms current rating of devices, one can avoid requirement of the 'Limit tracing Vector Control'. This greatly simplifies the control requirements of a Synchronous Link Converter, when used in the electric traction drive system.

5.7 Characteristics of the Converter for Reverse Power Flow :

In the preceding sections, application of Synchronous link converter to a 25 kV *ac* traction systems was presented for the forward power flow conditions. The characteristics will remain same for reverse power flow condition (during regeneration). This is due to the fact that harmonic voltages and harmonic currents at the converter input terminals are a function of modulation index and is independent of the phase of converter input voltage with respect to the supply voltage. For the reverse power flow the phase of converter input voltage is made to lead the supply voltage, and the modulation index remains almost constant (assuming the power level to be the same). Hence the psophometric current characteristics remains same for either directions of the power flow.

5.8 Advantages of Synchronous Link Converter as a Front end Converters in Modern Electric Traction Systems:

The applications of the Synchronous Link Converter in a 25 kV *ac* traction systems may result in the following advantages

1 Due to reduction in the magnitude of psophometric current, *dc* component, audio frequency component and high frequency component currents in the over head catenary, practically there is no interference with the track and the telecommunication equipments

2 Due to operation of the Synchronous Link Converter at near unity power factor, under forward and reverse power flow conditions, there is a reduction in the losses in over head catenary supply This results in the economic operation of traction sub stations

3 There is an increase in the life and a reduction in the maintenance of brake equipments, brake blocks, wheel tyres and control equipments, owing to the availability of regenerative braking from the maximum speed upto near stand-still condition.

4 The multi stage operation favours the utilization of leakage reactance of the traction transformer and results in the reduction in volume, weight, losses etc associated with an independent synchronous link inductor

5 The use of lower value of carrier frequency results in the better performance of GTO thyristors due to reduced switching losses.

6. The psophometric current is independent of the operating point(power output) of motor coaches.

7. There is no need for Var Compensator at the input terminals

8 There is no need for low frequency harmonic filters at the input terminals

Due to the above mentioned advantages, Synchronous Link Converters can be used as a front end converters in a Modern 25 kV Regenerative AC Traction Drive Systems

Chapter 6

Conclusion and Scope for future Work

The performance, design and analysis of a Single phase, Synchronous Link Converter has been presented

It has been shown that, to ensure the unity power factor operation of converter there is a limit on the maximum value of synchronous link inductance that can be used at a given power rating. Alternatively for a given value of synchronous link inductance, there is a maximum limit for the rms value of source current to ensure the unity power factor operation of the converter

Due to the use of indirect current control, the dominant harmonic appear at well defined frequencies The dominant harmonic frequencies in order of the amplitude are around $2f_c \pm f_s$, $4f_s \pm f_s$, $6f_c \pm f_s$, $8f_c \pm f_s$ and etc This consideration will limit the minimum modulation index around 0 7 for a single stage single phase Synchronous Link Converter. The maximum modulation index depends upon the turn off time of switching devices used.

Due to appearance of the dominant harmonics at well defined frequencies, the passive harmonic filters can be designed to suppress these harmonics from entering into the supply.

It has been shown that, the psophometric disturbance current reduces with the higher value of synchronous link inductance, higher value of the carrier frequency and with the increase in number of stages of synchronous link converters With the

increase in the number of stages, synchronous link reactance based on the transformer secondary KVA rating reduces Hence it can be easily realized by utilizing the leakage reactance of transformer secondary windings This is an additional advantage of multi stage Synchronous Link Converter

It has been shown that with the increase in number of stages, there is a possibility, that the switching devices rms current rating may fall within the power capability of currently available IGBT's This may lead to overall better performance of the multistage Synchronous Link Converter due to the higher switching frequency of IGBT's

The psophometric disturbance current remains constant with change in the power output from the converter Hence the harmonic characteristics of the motor coaches / locomotives remains same irrespective of the operating point

It has been shown that by the proper choice of synchronous link inductance, device rms current rating and the *dc* link voltage, one can easily avoid the use of 'Limit Tracing Vector Control'. In this way the multistage Synchronous Link Converter can be made to operate with a wide variations in catenary voltage by its own This greatly simplifies the control requirements

6.1 Scope for Future Work :

The work can be extended to study the performance and establish the design requirements of half controlled single phase and three phase Synchronous Link Converters

The psophometric disturbance current analysis can be extended with several stages of the half controlled single phase Synchronous Link Converters

The work can be extended to investigate the use of the three phase Synchronous Link Converter for a high horse power Diesel Electric Locomotive *ac* motor traction drive applications

The psophometric disturbance current analysis can be done to study the performance of front end converters with an unbalance loading of the *dc* links of a four stage Synchronous Link Converter Such a situation occurs at the start of the motor coaches / locomotives

Appendix I

I.1 Information related to Psophometric current Evaluation :

Harmonic number	Weightage Factor	Harmonic number	Weightage Factor	Harmonic number	Weightage Factor
1 0	0 0007	21 00	1 1090	41 0	0 6980
2 0	0 0090	22 00	1 0720	42 0	0 6890
3 0	0 0350	23 00	1 0350	43 0	0 6790
4.0	0.0890	24 00	1 0000	44 0	0 6700
5 0	0.1780	25 00	0.9770	45 0	0 6610
6.0	0 2950	26 00	0 9550	46 0	0 6520
7 0	0.3760	27 00	0 9280	47 0	0 6430
8 0	0 4840	28 00	0 9050	48 0	0 6340
9.0	0.5820	29 00	0 8810	49 0	0 6250
10 0	0.6610	30 00	0 8610	50 0	0 6170
11.0	0.7330	31 00	0.8420	51 0	0 6070
12 0	0.7940	32 00	0.8240	52 0	0 5980
13 0	0 8510	33 00	0 8070	53 0	0 5900
14.0	0 9020	34 00	0 7910	54 0	0 5800
15.0	0.9550	35 00	0 7750	55 0	0 5710
16 0	1 0000	36 00	0 7600	56 0	0 5620
17.0	1.0350	37 00	0 7450	57 0	0 5530
18.0	1.0720	38 00	0 7320	58 0	0 5430
19 0	1 1090	39 00	0 7200	59 0	0 5250
20.0	1 1220	40 00	0 7080	59 0	0 5250

Table I 1: Weightage Factor Chart

Appendix II

II.1 Component Specification for Control and Drive Circuit :

Control Circuit	
IC1, IC7, IC10	LM 324 Quad Comparator
IC2	CD 4046 Micro Power Phase Lock Loop
IC3, IC4	CD 4040 Binary Counter
IC5	INTEL 2732 EPROM
IC6	DAC 08 Digital to Analog Converter
IC8, IC9, IC11	CD 4047 Low Power Monostable Multivibrator
IC12	LM 565 Phase Locked Loop
IC13, IC14	TL08 Operational Amplifier
IC15, IC16	LM 311 Comparator
IC17	CD 4081 Quad two input AND Gate
IC18, IC19	CD 4049 Hex Inverter
D1, D2, D3 ,D4	IN4148 Diode
PT1, PT2	47 K pot
T1, T2, T3, T4	SL100 Transistor
R1 - R4, R18 - R21	12 K, 1/4 watt
R5, R8 - R10,R17	5.6 K 1/4 watt
R6, R7	15 K 1/4 watt
R11, R12, R14 - R16	12 K, 1/4 watt
R13	1 2 K 1/4 watt + 47 K pot
R22, R23	33 K 1/4 watt

R24 - R30	10 K 1/4 watt
R32 - R36, R43, R44	12 K, 1/4 watt
R40	560 K, 1/4 watt
R41, R42	1 2 K, 1/4 watt
R43	12 K 1/4 watt + 47 K pot
R45 - R48	12 K, 1/4 watt
R49, R50	150 K, 1/4 watt
C1	2 KpF
C2	1μF
C3, C5, C6	1 KpF
C4	0 04 μF
C7	0 01 μF
C8	10 KpF
C9	0 05μF
C10, C11	82 pF
<u>Driver Circuit</u>	
Rg	100 Ω, 1/2 watt
R2, R3	1 2 K, 1/4 watt
R1	12 K, 1/4 watt
C	47 μF 25 V Electrolytic Capacitor
D1	IN4007 Diode
OP1	4N35 Opto Coupler

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